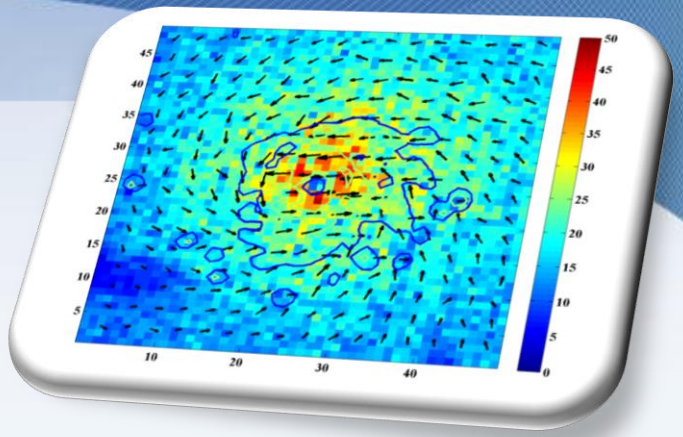


"Q-Winds" Hurricane Retrieval Algorithm using QuikSCAT Scatterometer

Pete Laupattarakasem

Doctoral Dissertation Defense

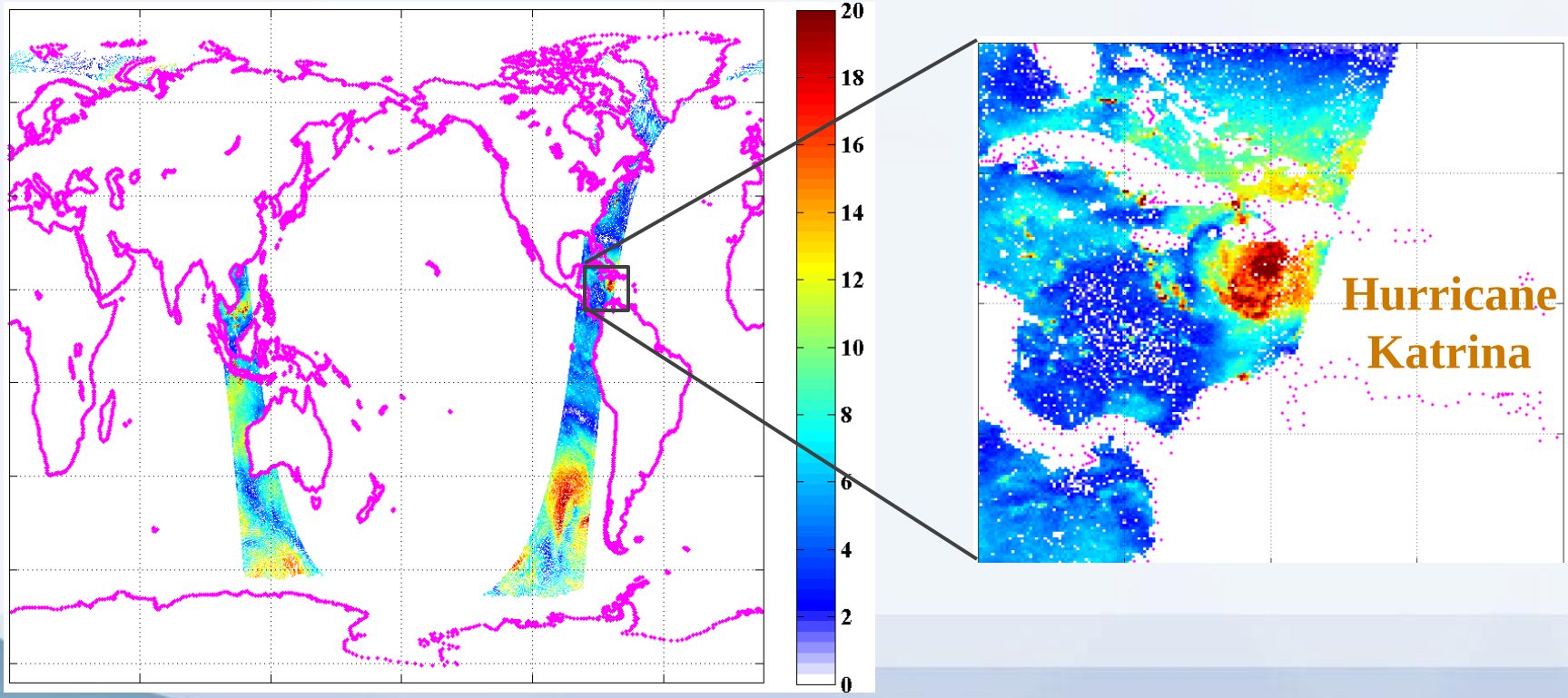
March 23rd, 2009

Presentation Outline

- Dissertation Objective
- Background
  - Scatterometry/Radiometry
  - SeaWinds on QuikSCAT
  - Wind Scatterometry
- Current Ocean Vector Winds Products
  - HRD H*Wind Analysis
  - JPL L2B & L2B-12.5km
- Q-Winds Hurricane Algorithm
- Hurricane Retrieval Results
- Summary & Conclusion

Introduction

- *Scatterometers* measure ocean surface wind vectors
  - Remotely infers winds from ocean radar backscatters (sigma-0) at multiple azimuth directions
  - Global measurements for all weather & day/night



Current Issues for TC Wind Vectors Measurements

- Underestimates peak wind speeds estimations in TC
  - Occasionally overestimates winds because of rain contamination
- Incorrect wind direction selection
  - Selects wrong solution in presence of rain
    - Miss-locates hurricane eye
- Unreliable rain flags
  - Discards both rain contaminated data & desired high wind data

Dissertation Objective

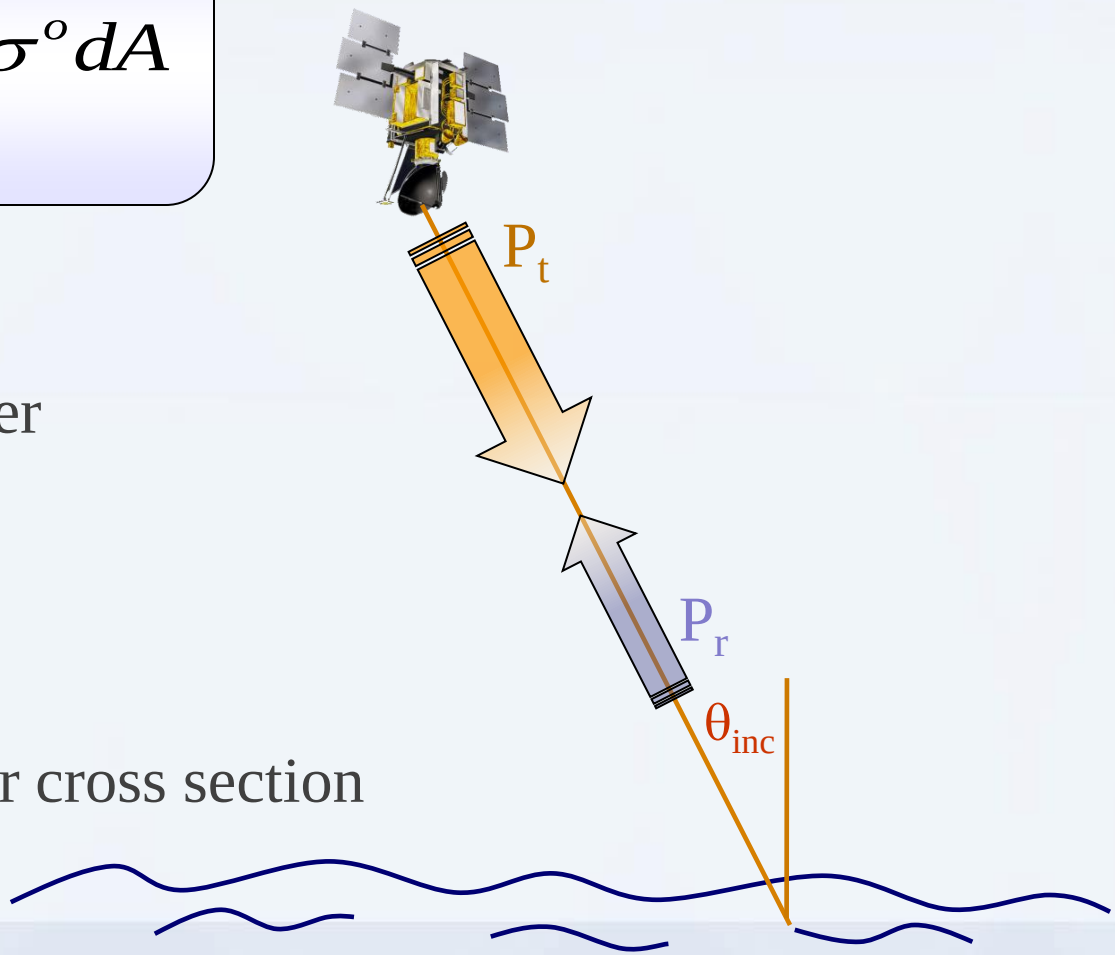
- To develop robust hurricane wind vector retrieval algorithm for *QuikSCAT* that uses existing JPL data products to:
  - Improve wind vector retrievals
    - Tailored to extreme wind events
    - Incorporates rain attenuation & rain volume scattering
    - Provides reliable rain flags
  - Provide near real-time data products for operational hurricane surveillance

Microwave Scatterometry: Scatterometer

Scatterometer: Special radar to measure ocean σ^0

$$P_r = \frac{P_t \lambda^2}{(4\pi)^3} \iint_A \frac{G^2}{R^4} \sigma^o dA$$

- Pr = received power
- Pt = transmitted power
- G = antenna gain
- R = range
- λ = wavelength
- σ^0 = normalized radar cross section (NRCS)



Microwave Scatterometry: Principle

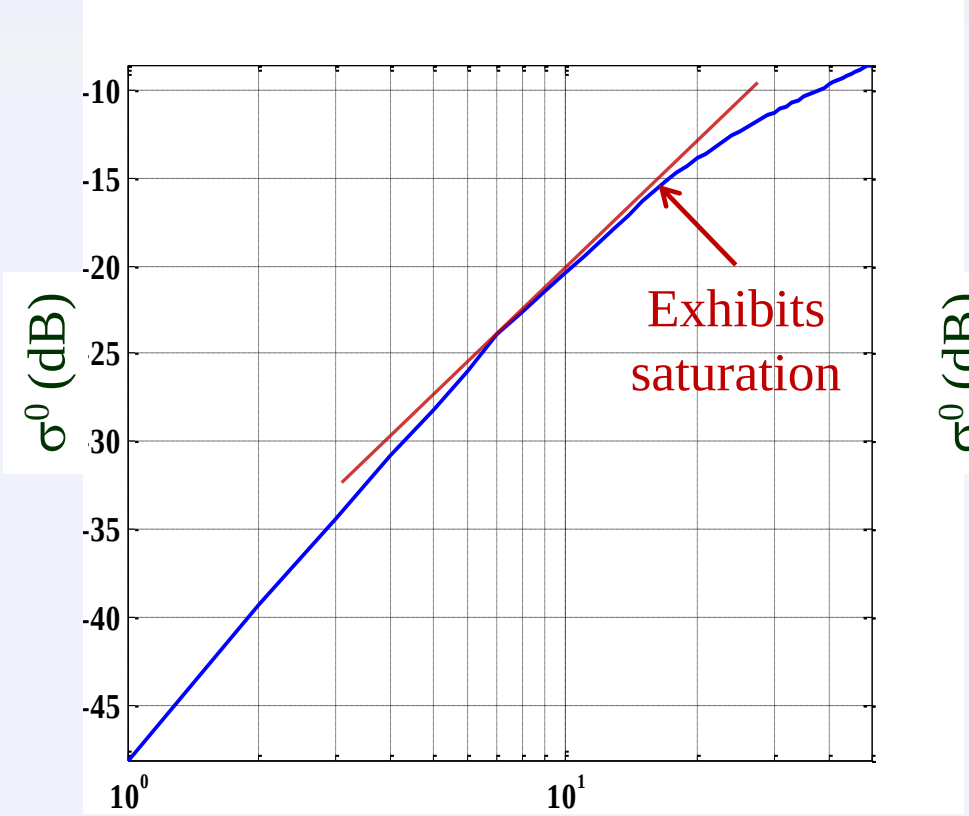
- Ocean sigma-0, σ^0, response
  - Resonant Bragg scatterings
    - Capillary waves (2-3 cm wavelength)
  - Increases with wind speed
  - Varies with relative wind directions (anisotropic)

- Sigma-0 & wind vector relates through *geophysical model function (GMF)*

$$\sigma^0 = f(ws, \chi, freq, \theta_{inc}, pol)$$

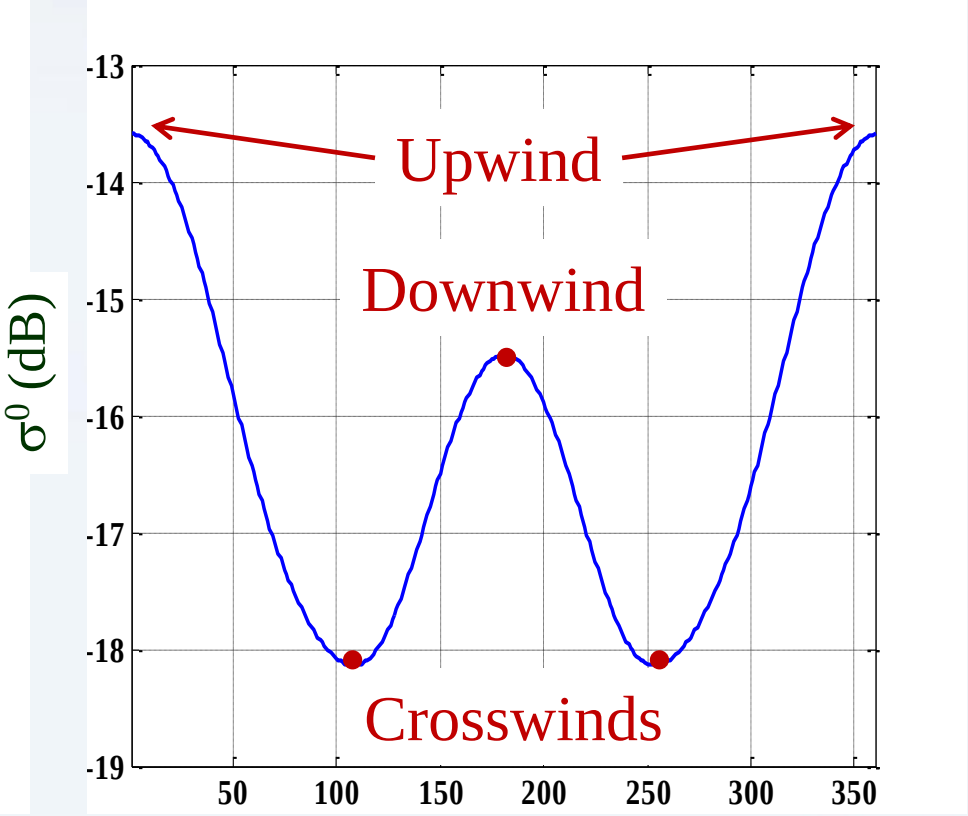
Ocean Sigma-0 Response to Wind

Wind Speed Response



Wind Speed

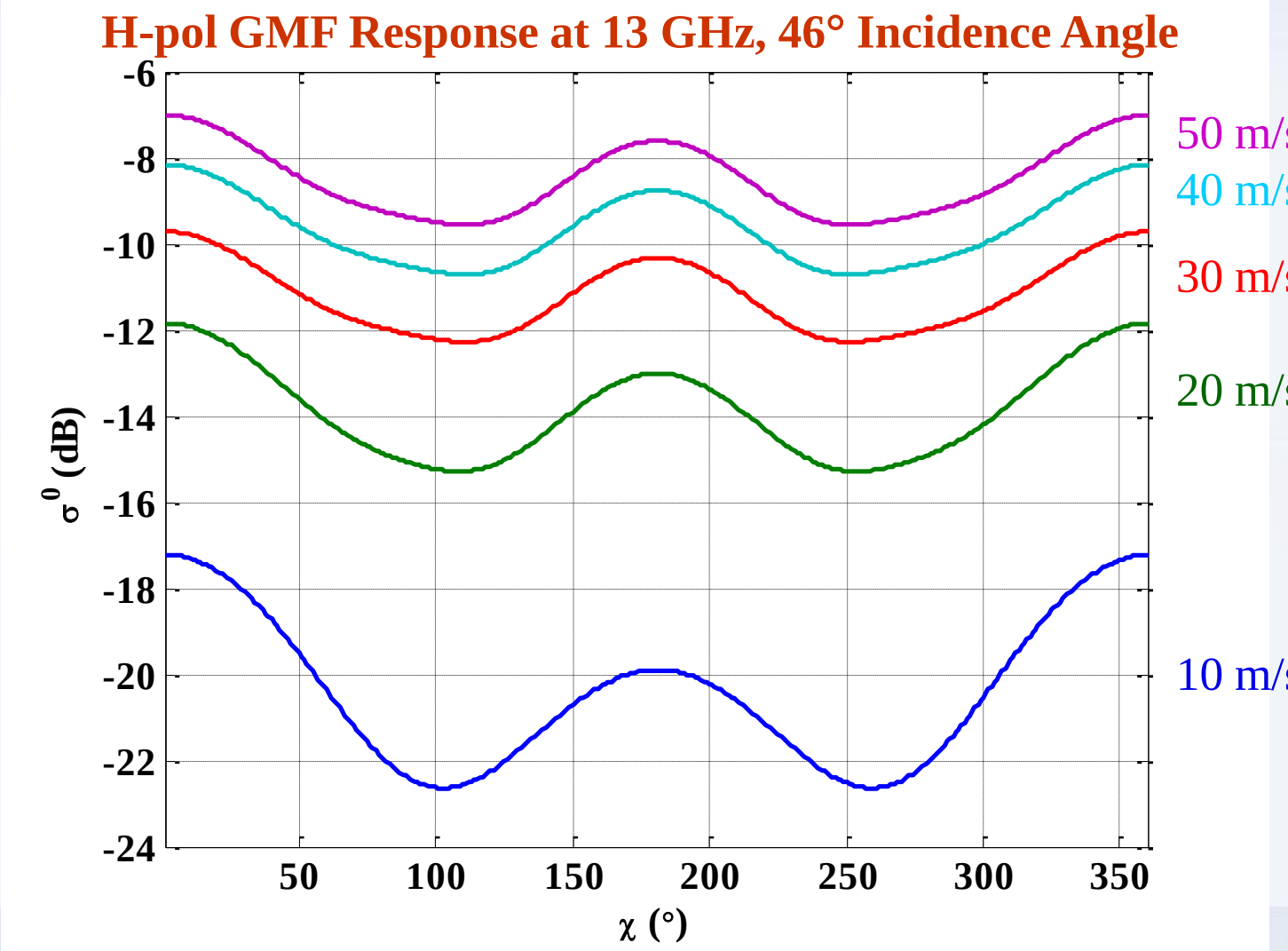
Wind Direction Response



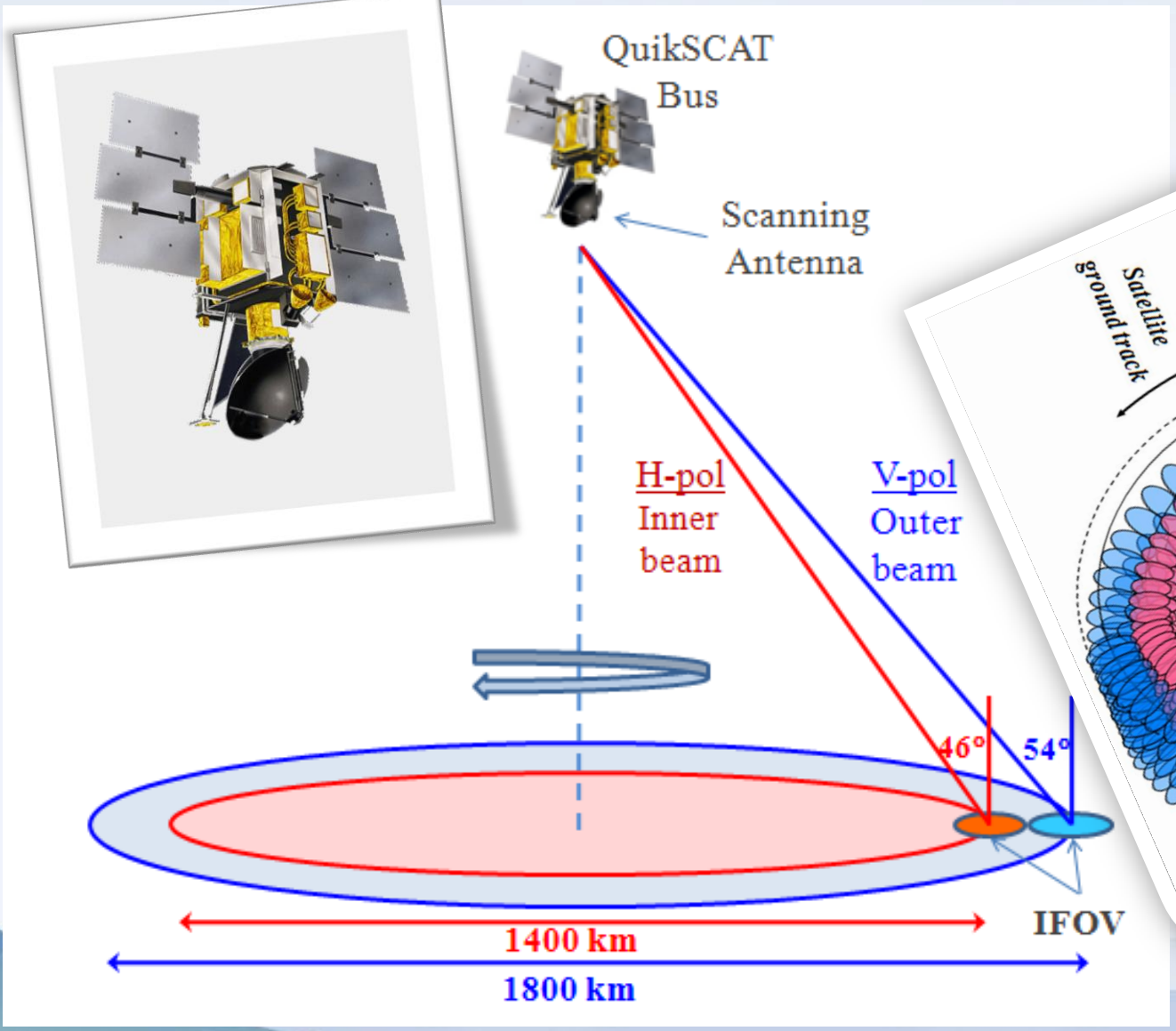
Relative Wind Direction, χ

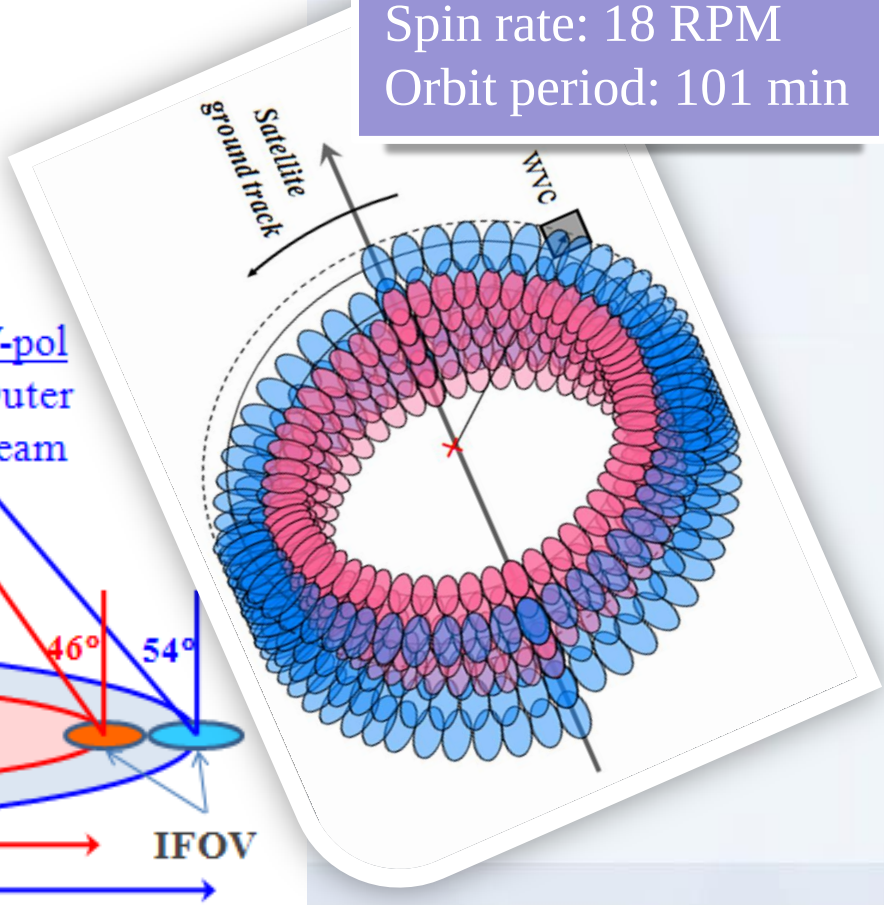
χ = Azimuth angle – Wind direction

Geophysical Model Function (GMF)



SeaWinds on QuikSCAT





Name: QuikSCAT
Date: 1999 - Present
Frequency: 13.4 GHz
Spin rate: 18 RPM
Orbit period: 101 min

Microwave Radiometry: Principle

- Radiometer measures blackbody spectral radiance

$$P_r = \mathrm{k} \times T_b \times B$$

where $\mathrm{k} \equiv$ Boltzmann's constant

$T_b \equiv$ Brightness temperature

$B \equiv$ Receiver bandwidth

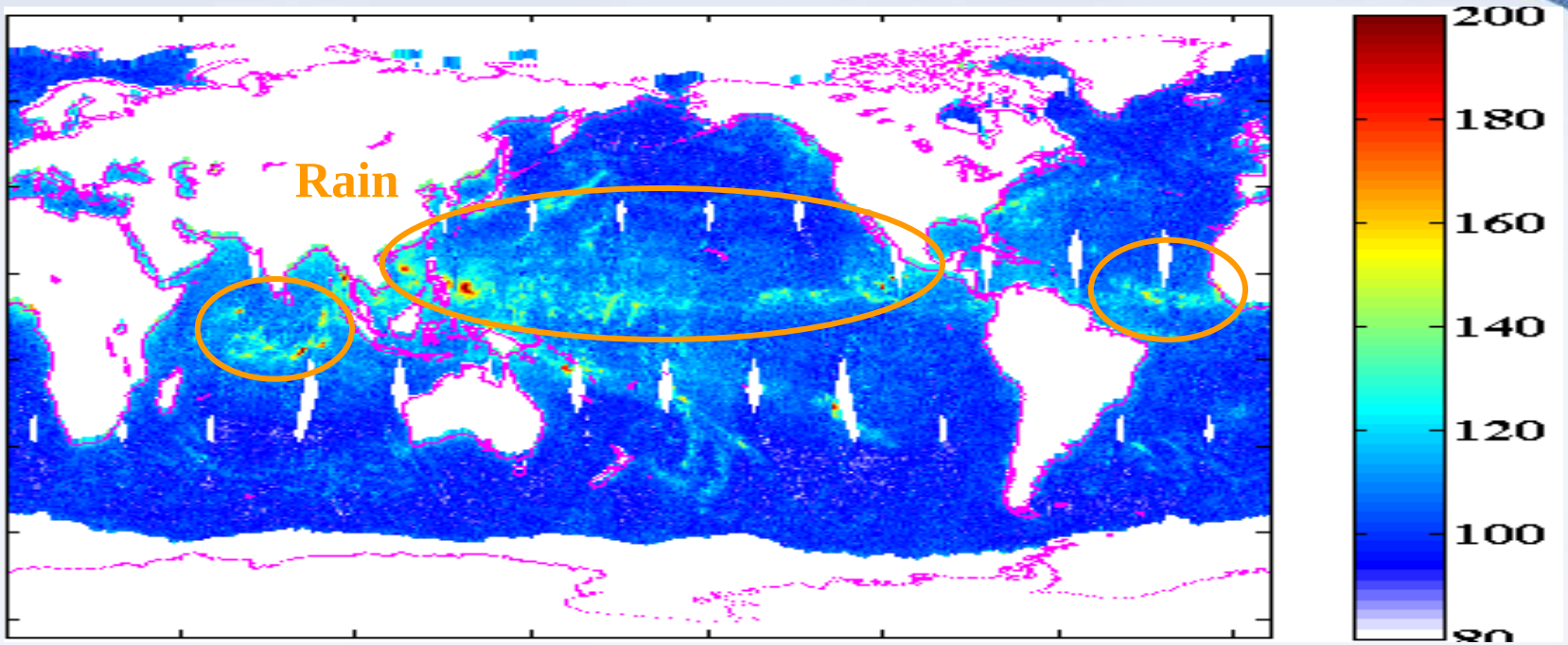
- By Rayleigh-Jeans approximation, linear relationship between received power & emissivity, ε, in μ-wave region

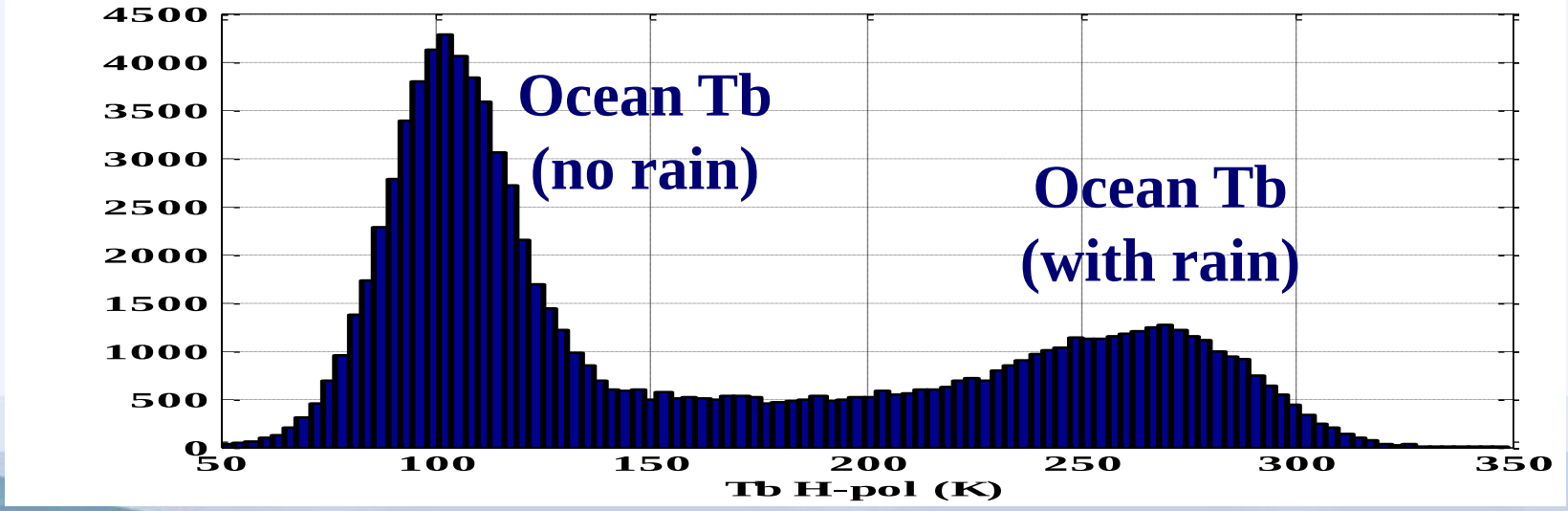
$$T_b = \varepsilon \times T_{phy}$$

SeaWinds as a Radiometer

- *QuikSCAT Radiometer (QRad)* is radiometric function implemented through ground processing
  - Trained & externally calibrated using collocated SeaWinds & TRMM Microwave Imager (TMI)
  - Not optimum radiometer ($\Delta T \sim 27$ K/pulse)
  - Used to derive rain rate called *QRad rain rate* algorithm
  - QRad Tb & QRad rain rate are included in L2A & L2B products

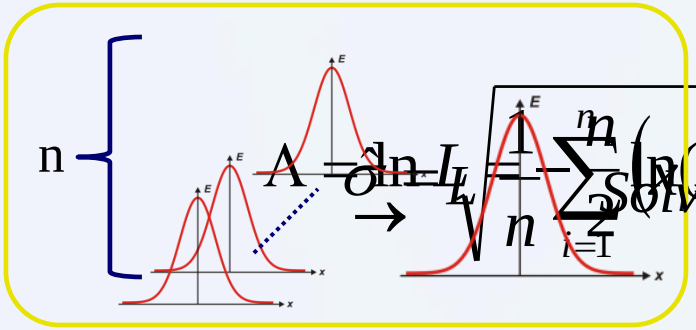
QRad T_b & QRad Rain Rate





Wind Vector Retrieval Algorithm

- Standard process for wind vectors measurements
  - Zero-mean Gaussian measurements noise
  - Statistical process, e.g., maximum likelihood estimation (MLE)
  - Multi-azimuth looks observation
- Maximum Likelihood Estimation
  - Estimates parameters that maximize likelihood probability



$$\Lambda = \ln L_L = -\frac{n}{2}\ln(2\pi) - n\ln(\sigma) - \frac{1}{2}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{\sigma}\right)^2$$

$$\rightarrow \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{solve } \frac{\partial(\Lambda)}{\partial x} \;\&\; \frac{\partial(\Lambda)}{\partial \sigma} \quad \text{solution} = \min\left(\sum(\cdot)^2\right) \exp\left(-\frac{1}{2}\sum_{i=1}^{n}\left(\frac{x_i - \bar{x}}{\sigma}\right)^2\right)$$

MLE Wind Vector Retrieval

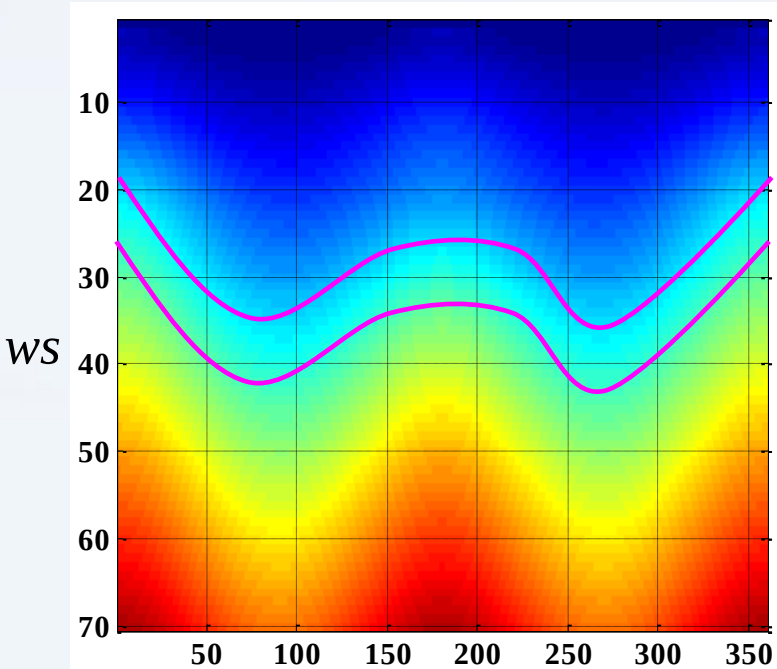
- MLE Objective Surface, ξ

$$\xi = \sum_{i=1}^{N} \left(\frac{\sigma^0_{i\ Meas} - \sigma^0_{i\ Mod}}{\delta_i} \right)^2$$

$$\sigma^0_{Mod} = GMF(ws, \chi, \text{freq}, \theta_{inc}, \text{pol})$$

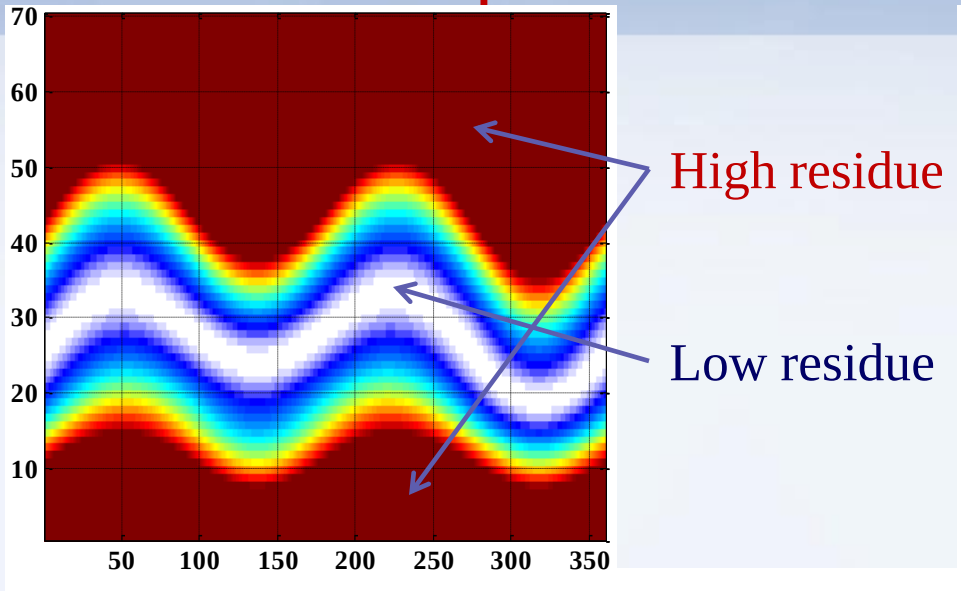
- N = number of measurements
- σ^0_{Meas} = Measured ocean σ^0 value
- σ^0_{Mod} = Modeled σ^0 from GMF table

σ^0_{Mod} Solution Space

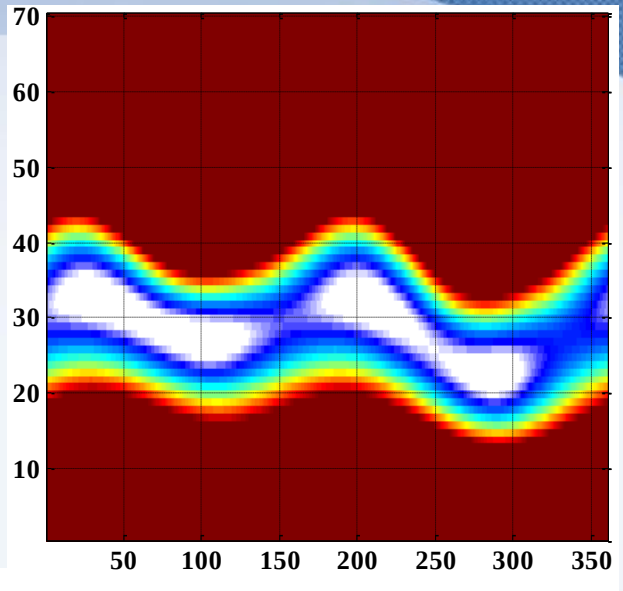


σ^0_{Meas} =

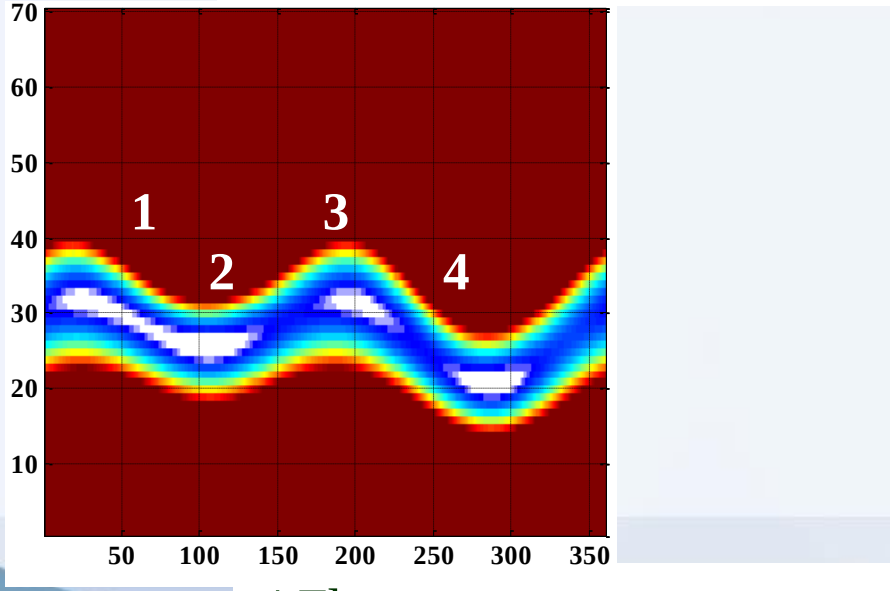
Multiple Azimuth Looks MLE



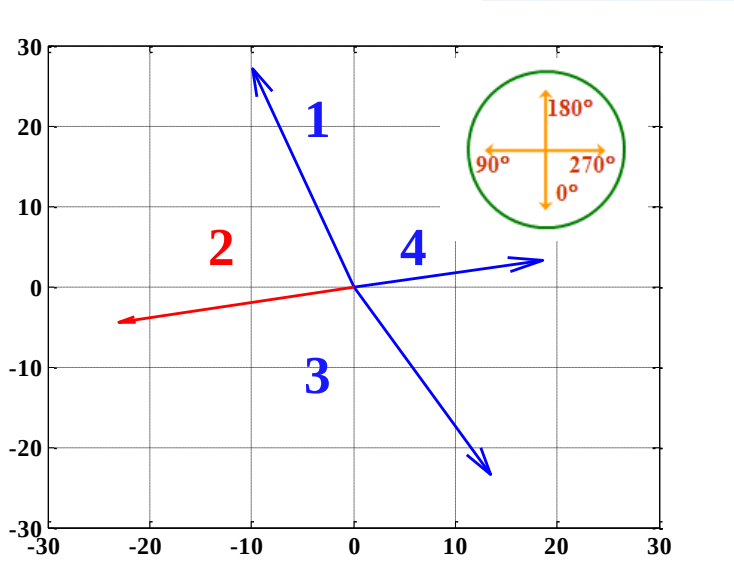
1 Flavor



2 Flavors



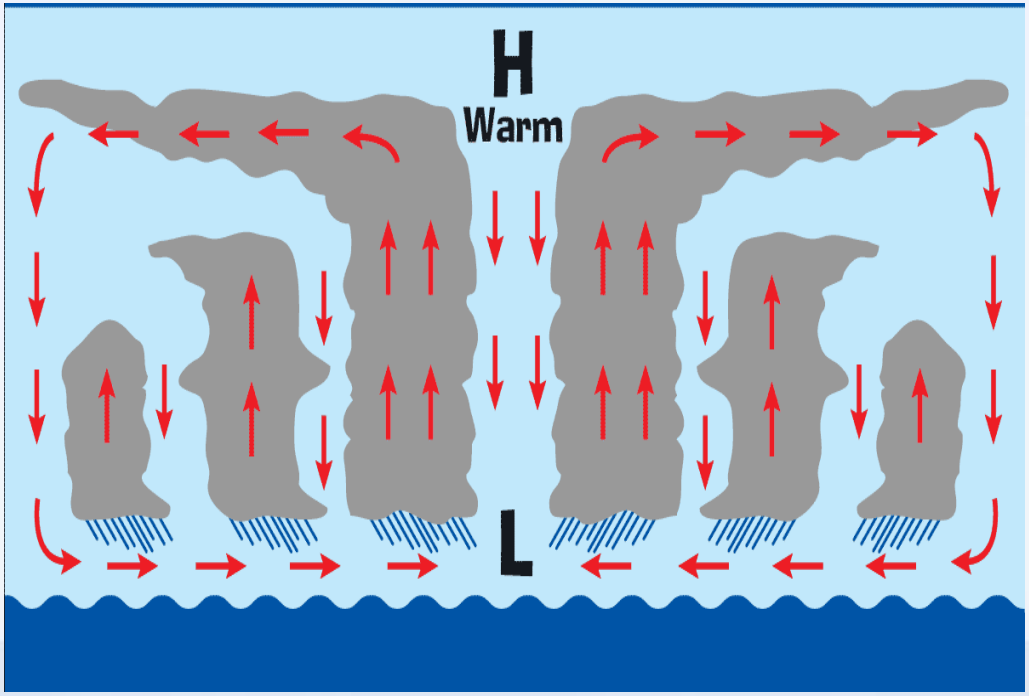
4 Flavors



Wind Vector Solutions

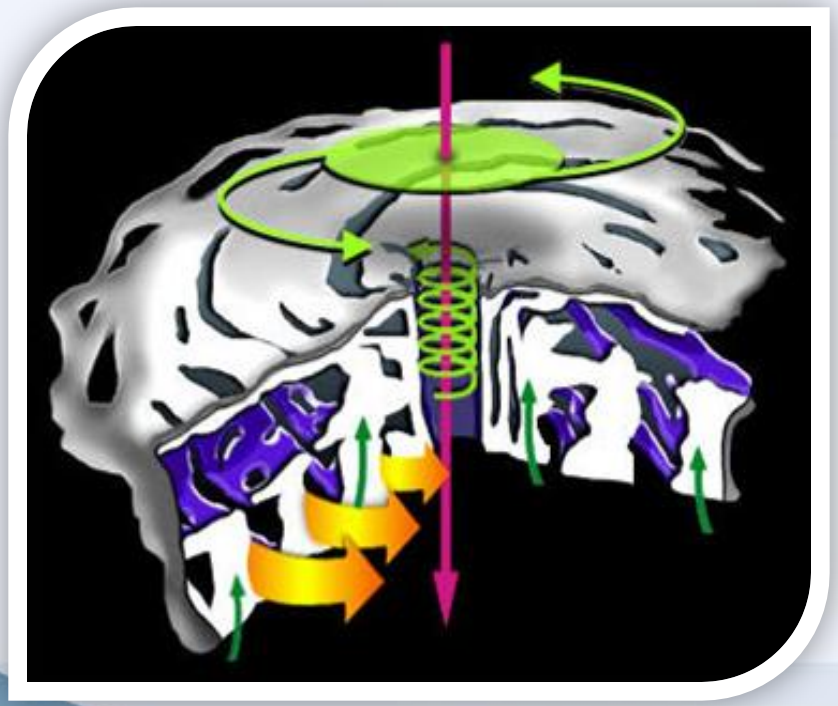
Hurricane Formation

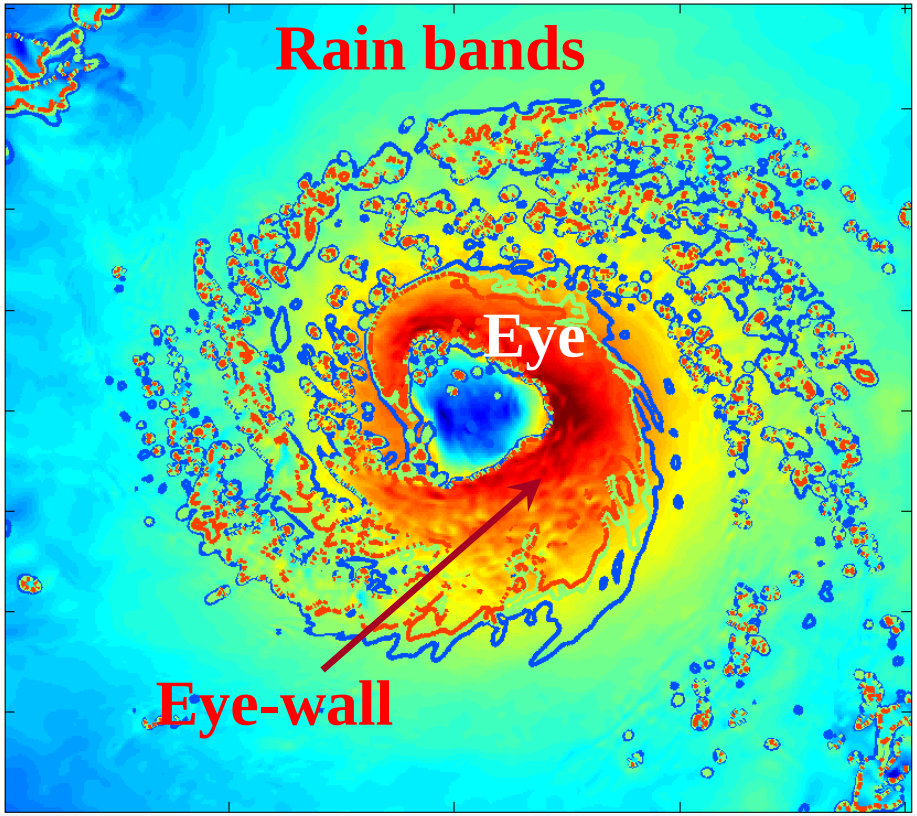
- Thunderstorms develop into hurricane when conditions are favorable
  - Warm water, open sky, away from land
- Hurricane sustains by heat transfer process



Anatomy of Hurricane

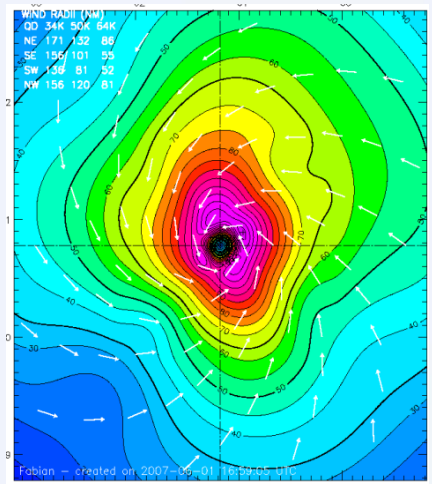
- Hurricane comprises of
  - Calm eye
  - Eye-wall
  - Spiral rain bands



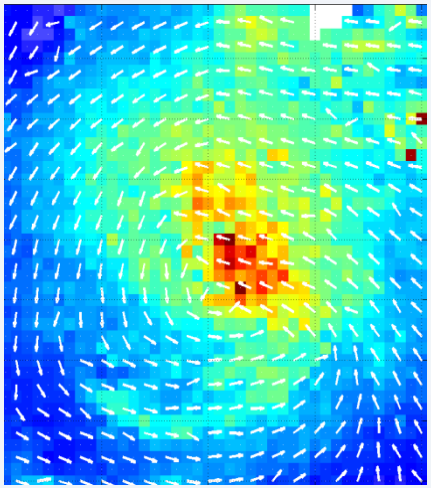


Courtesy of NASA's Observatorium

Current Ocean Vector Winds (OVW) Products



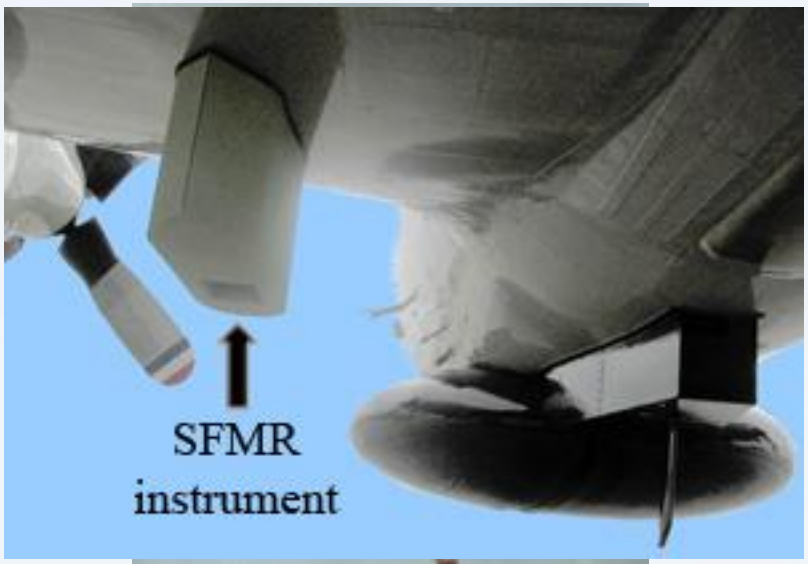
- HRD H*Wind Surface Analysis
- NASA JPL L2B Data Product



NOAA HRD H*Wind Surface Analysis

- Hurricane Wind Analysis System "*H*Wind*"
  - Real-time integrated TC observation system from multiple wind measurement platforms
    - Aircraft
      - SFMR *
      - GPS dropsondes *
      - Tail Doppler Radar
    - Satellite
      - QuikSCAT
      - ASCAT
      - WindSat

    * denotes high quality data

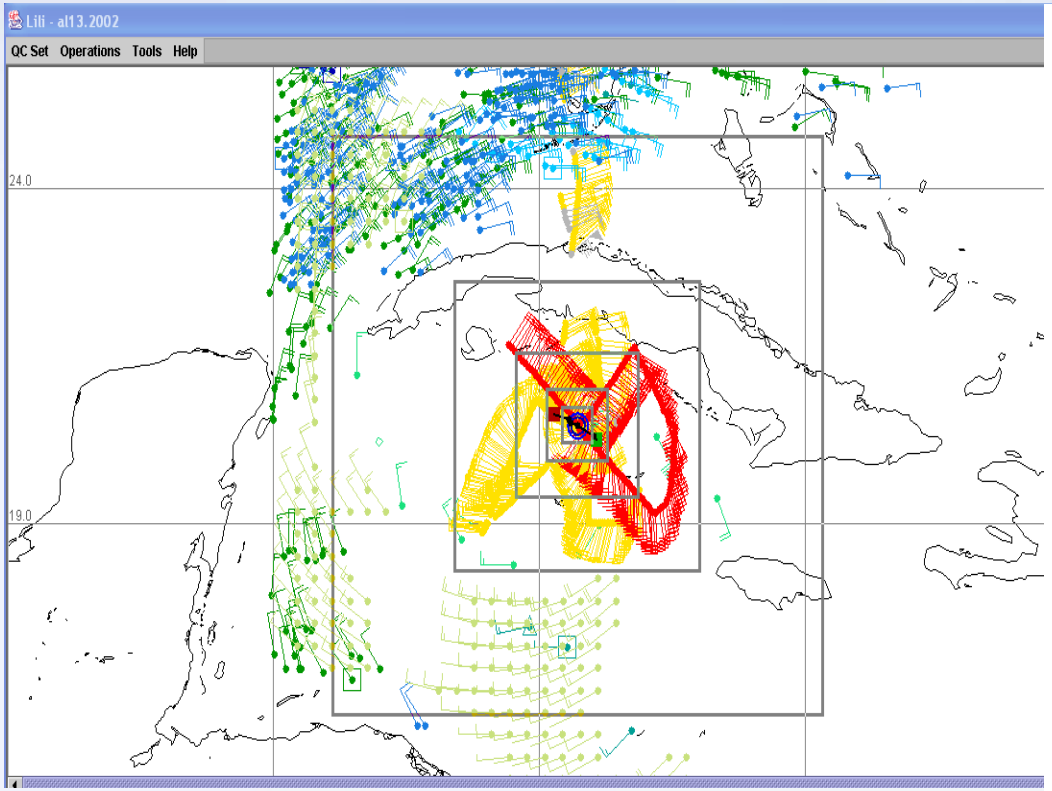


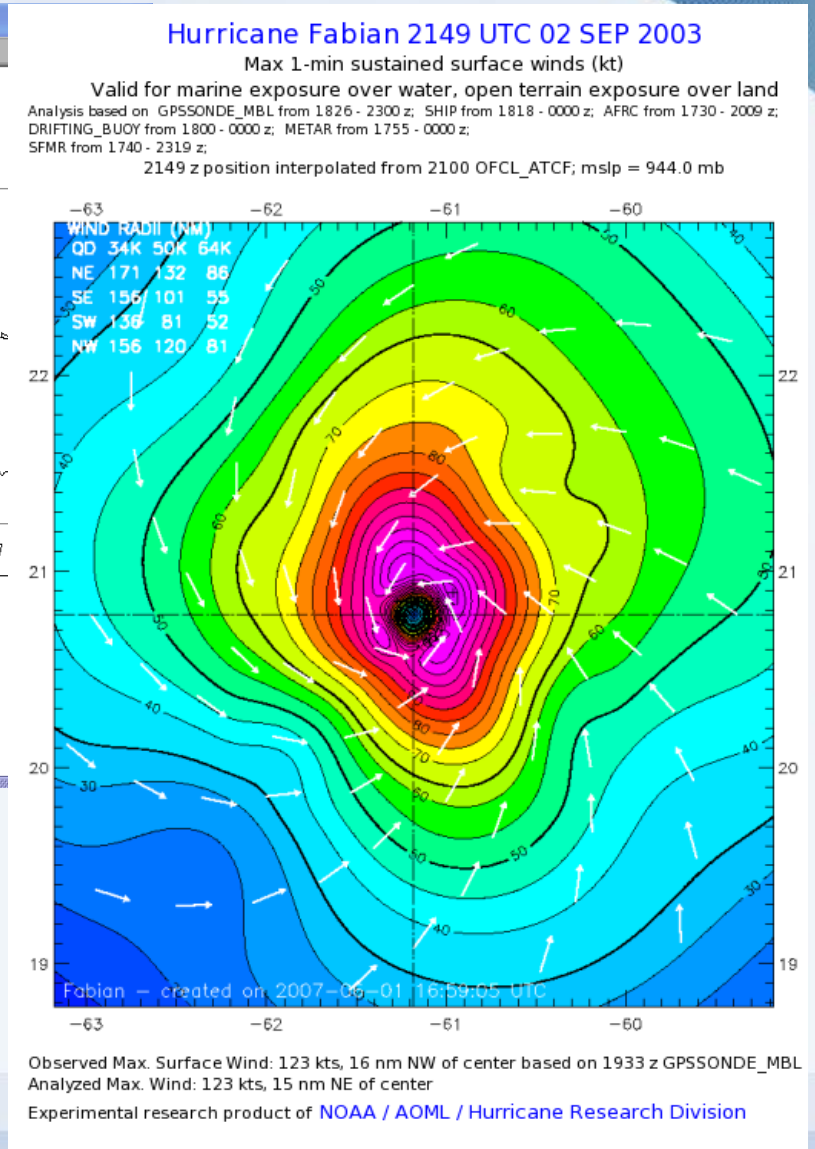
SFMR on NOAA WP-3D Hurricane Hunter Aircraft

GPS Dropwindsonde

- Current most trustable surface truth

NOAA HRD H*Wind Surface Analysis (cont.)

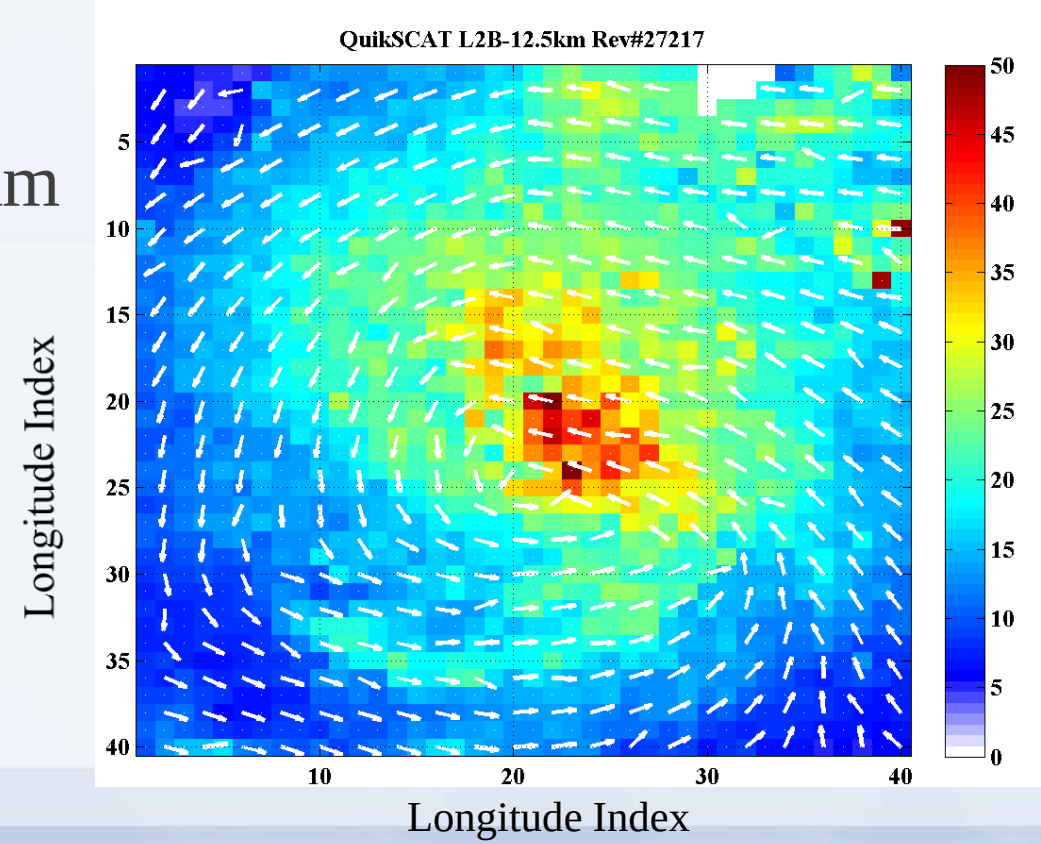




- High resolution (6 km) hurricane surface wind field, (1-min average)

JPL QuikSCAT L2B & L2B-12.5km OVW

- Standard OVW product derived from measured σ^0's for global scale
- Measures synoptic-scale winds
- No rain correction
- Available in 25 & 12.5 km

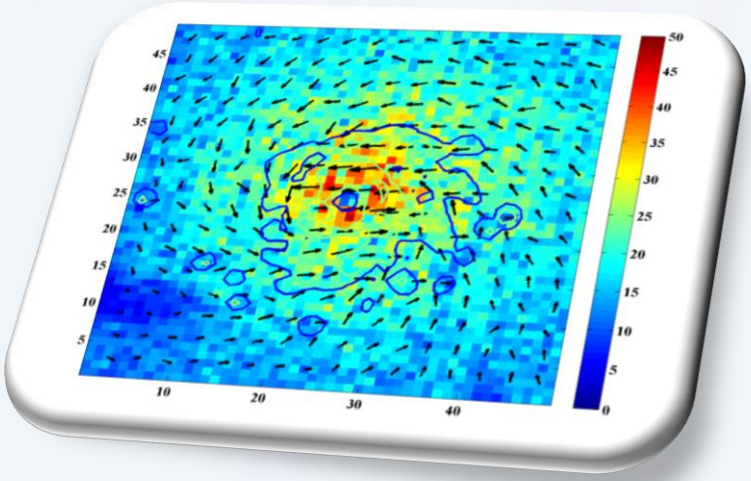


Q-Winds Hurricane Retrieval Algorithm

- Rain Effects Correction
- GMF Development for TC
- Aliases Selection
- Quality Control Flagging

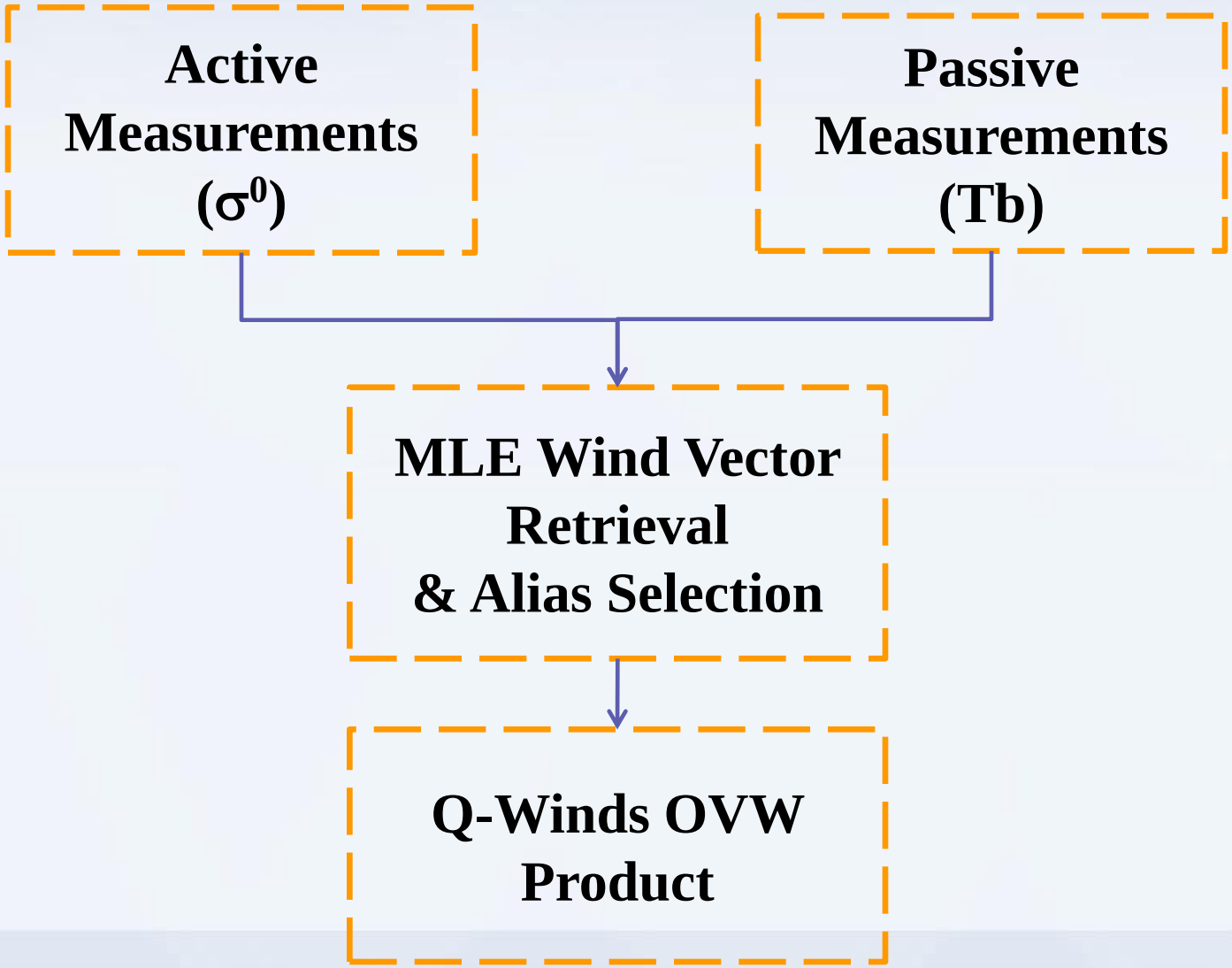
Q-Winds Highlight Features

- Q-Winds is the <u>only</u> wind retrieval algorithm that uses Tb
  - Combined active/passive measurements to estimate ocean surface backscatter
- Special GMF exclusively developed for TC's
- "Smart" wind direction selection
- Effective "excess-rain" flagging

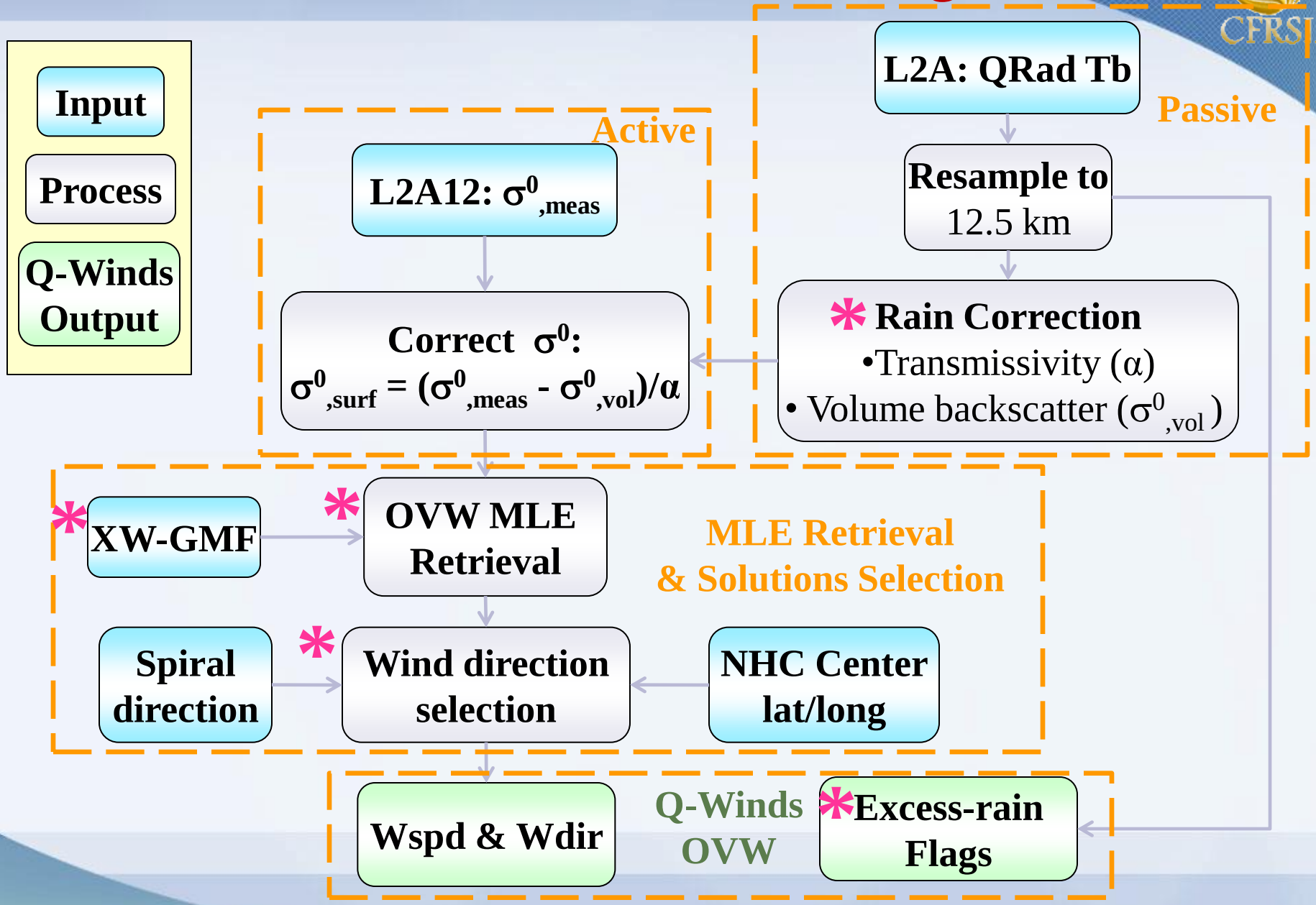


Q-Winds

Q-Winds Hurricane OVW Algorithm



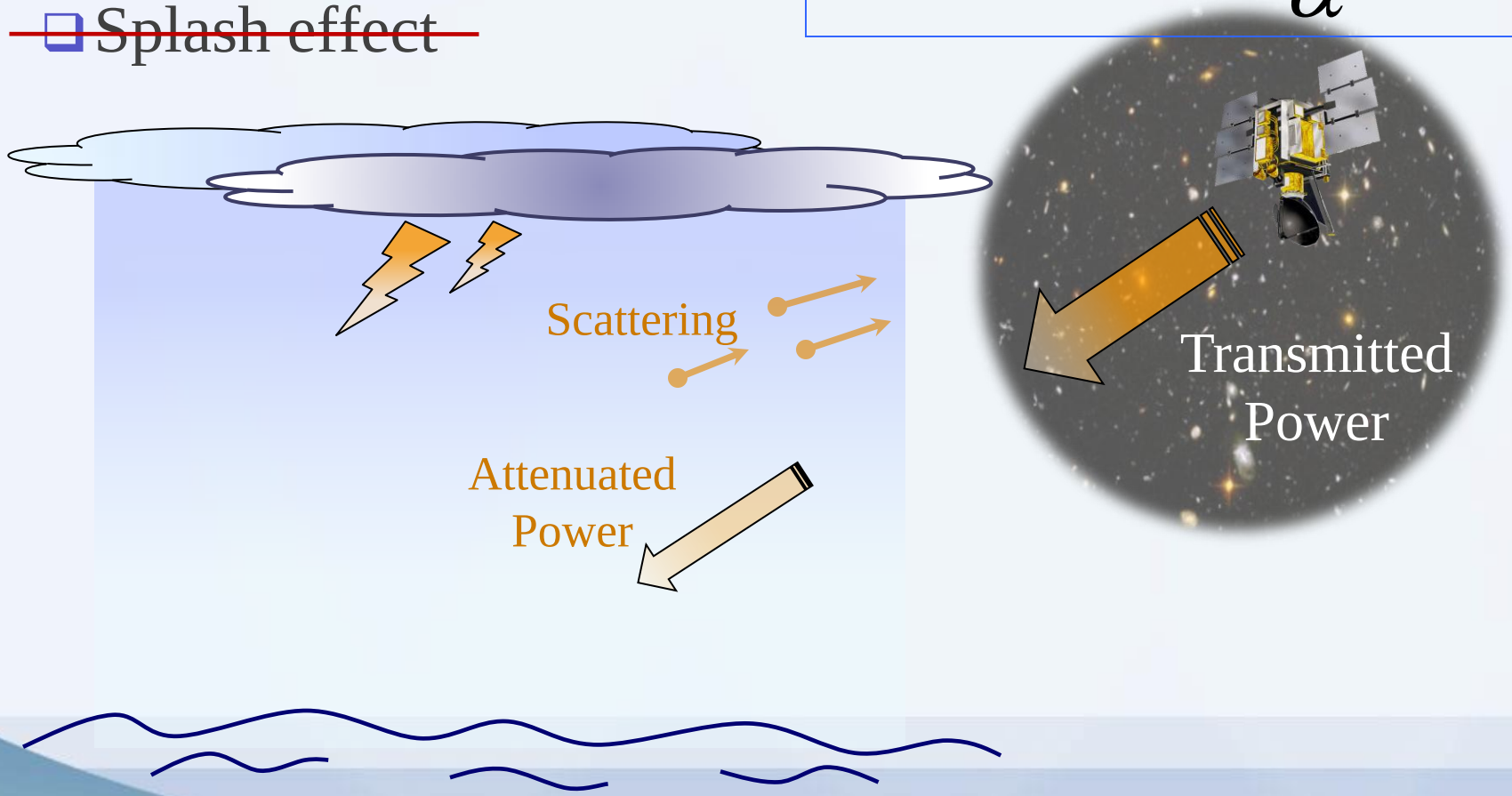
Q-Winds Hurricane OVW Algorithm



Rain Effects Correction

- Rain affects ocean σ^0 in three ways
  - Attenuation
  - Rain volume backscatter
  - ~~Splash effect~~

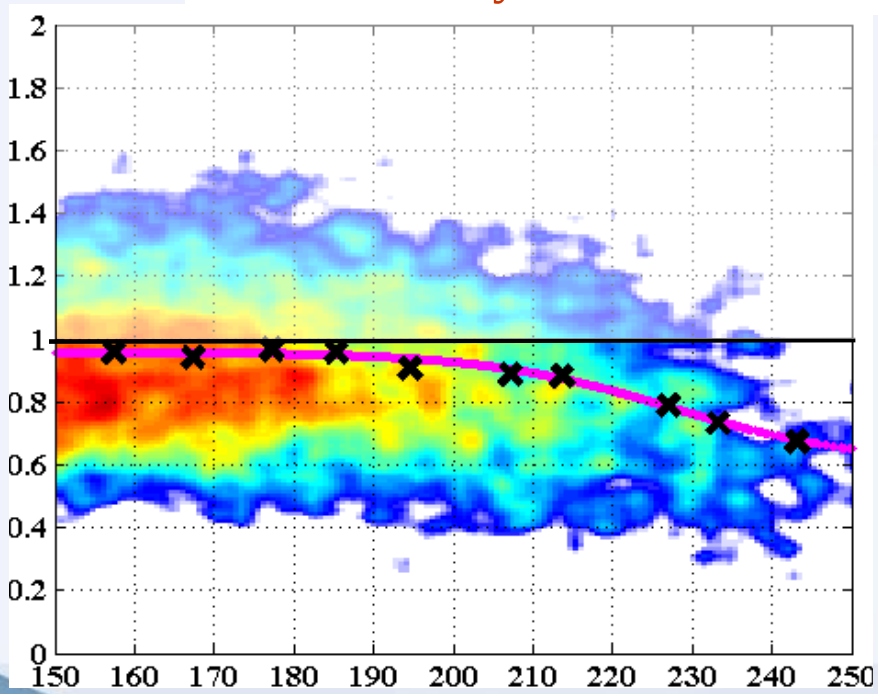
$$\sigma^0_{Surf} = \frac{\sigma^0_{Meas} - \sigma^0_{Rain}}{\alpha}$$



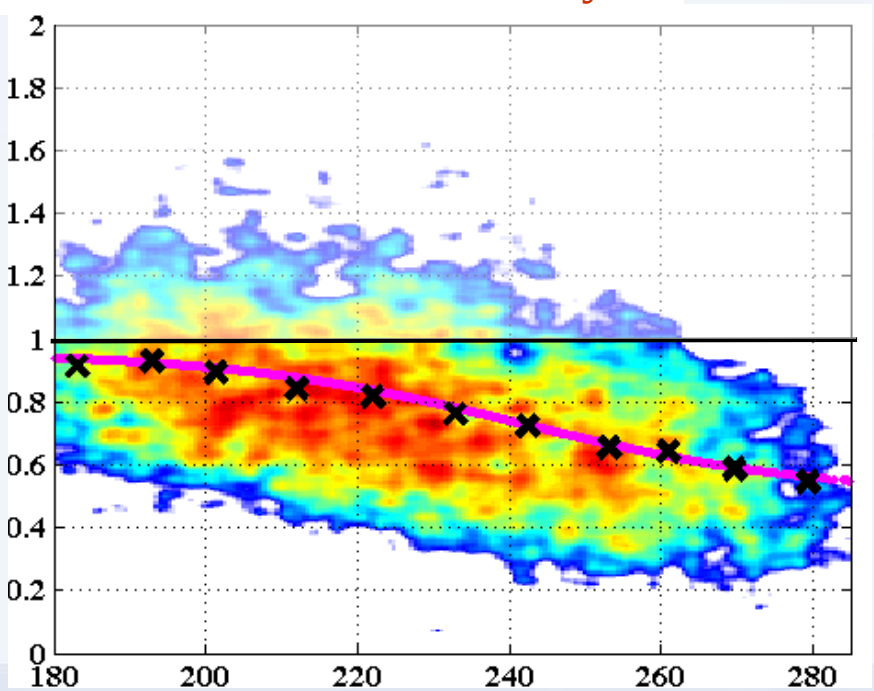
Rain Effects Correction

- *Transmissivity*, *T*, is "opaqueness" of atmosphere
  - Integrated rain effects (attenuation & volume backscatter)
  - Estimated ocean surface σ^0, σ^0_{Est}, from H*Wind
  - Modeled as ratio of σ^0_{Est} & σ^0_{Meas} with Tb

Transmissivity-H



Transmissivity-V



Tb-H

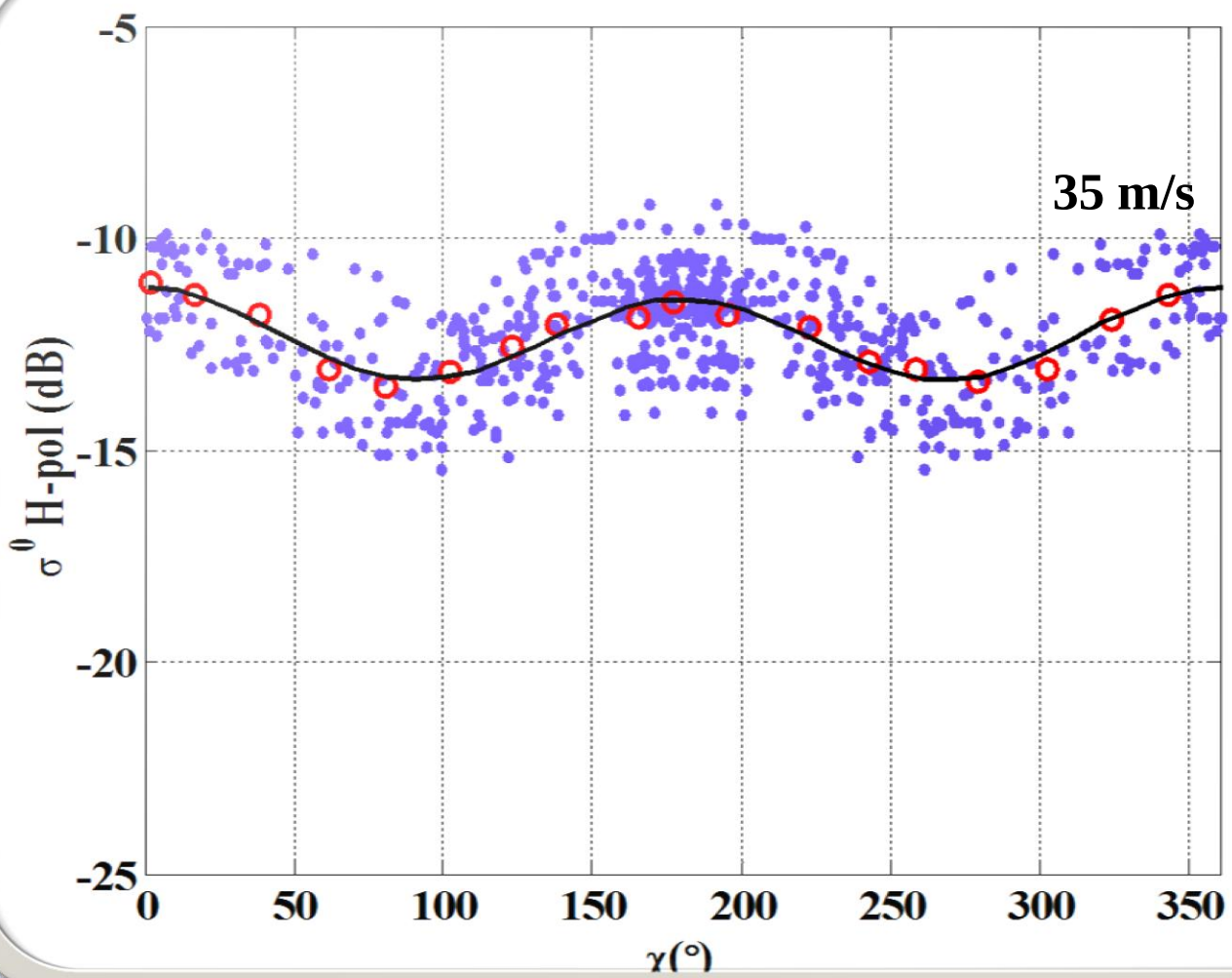
Tb-V

Extreme Winds GMF (XW-GMF)

- Current Ku-band scatterometer GMF's are not well-suited for TC wind conditions
  - Trained using "synoptic-scale" (~100 km) wind from numerical weather models
    - 99% of ocean winds are < 15 m/s
    - Exhibits strong σ^0 saturation when wind speed > ~30 m/s
- XW-GMF Development
  - Collocate QuikSCAT & H*Wind data from 18 hurricane events
    - Spatial resolution of 12.5 km
    - High quality surface truth includes SFMR & GPS dropwindsonde
    - Restricted to rain-free & light rain

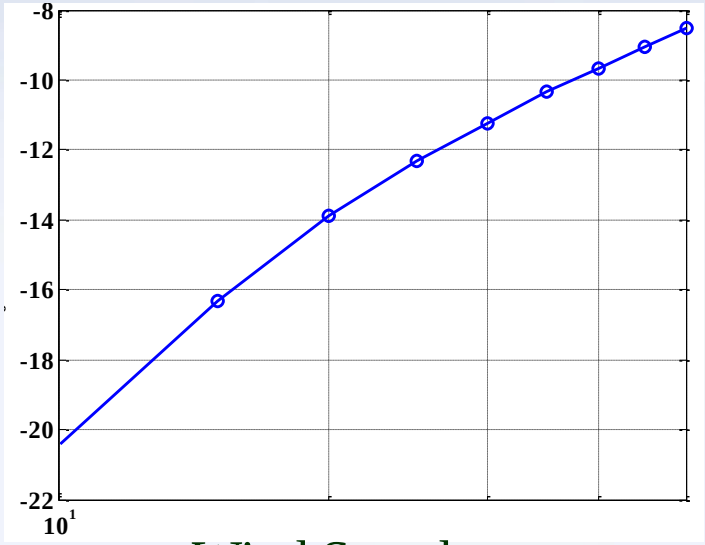
Sigma-0 Response Modeling

$$XW - GMF(ws, \chi) = C_0(ws) + C_1(ws)\cos(\chi) + C_2(ws)\cos(2\chi)$$



XW-GMF Construction (H-pol)

C_0

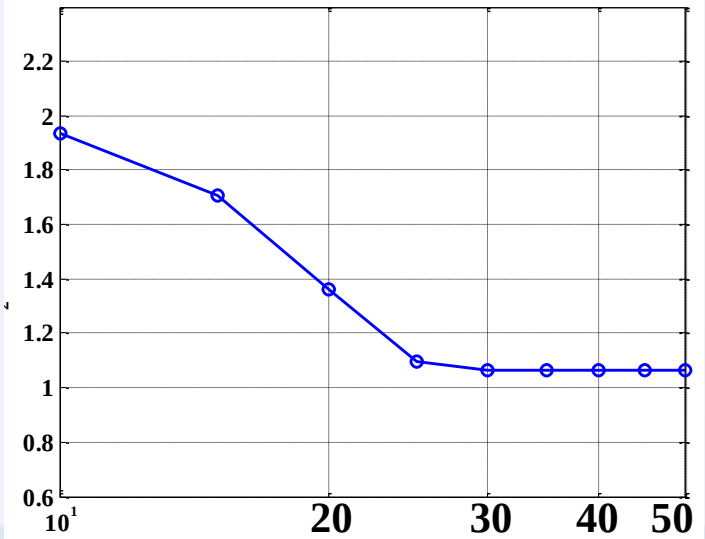


Wind Speed

C_1

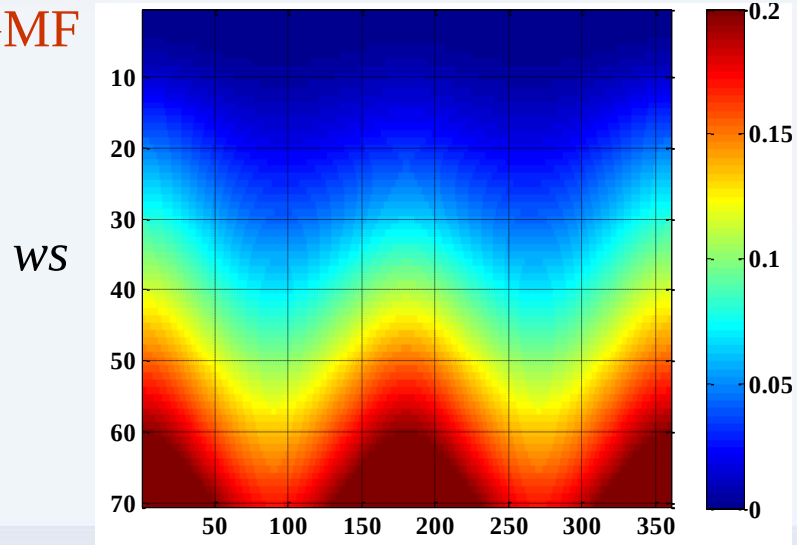
Wind Speed

C_2



Wind Speed

XW-GMF



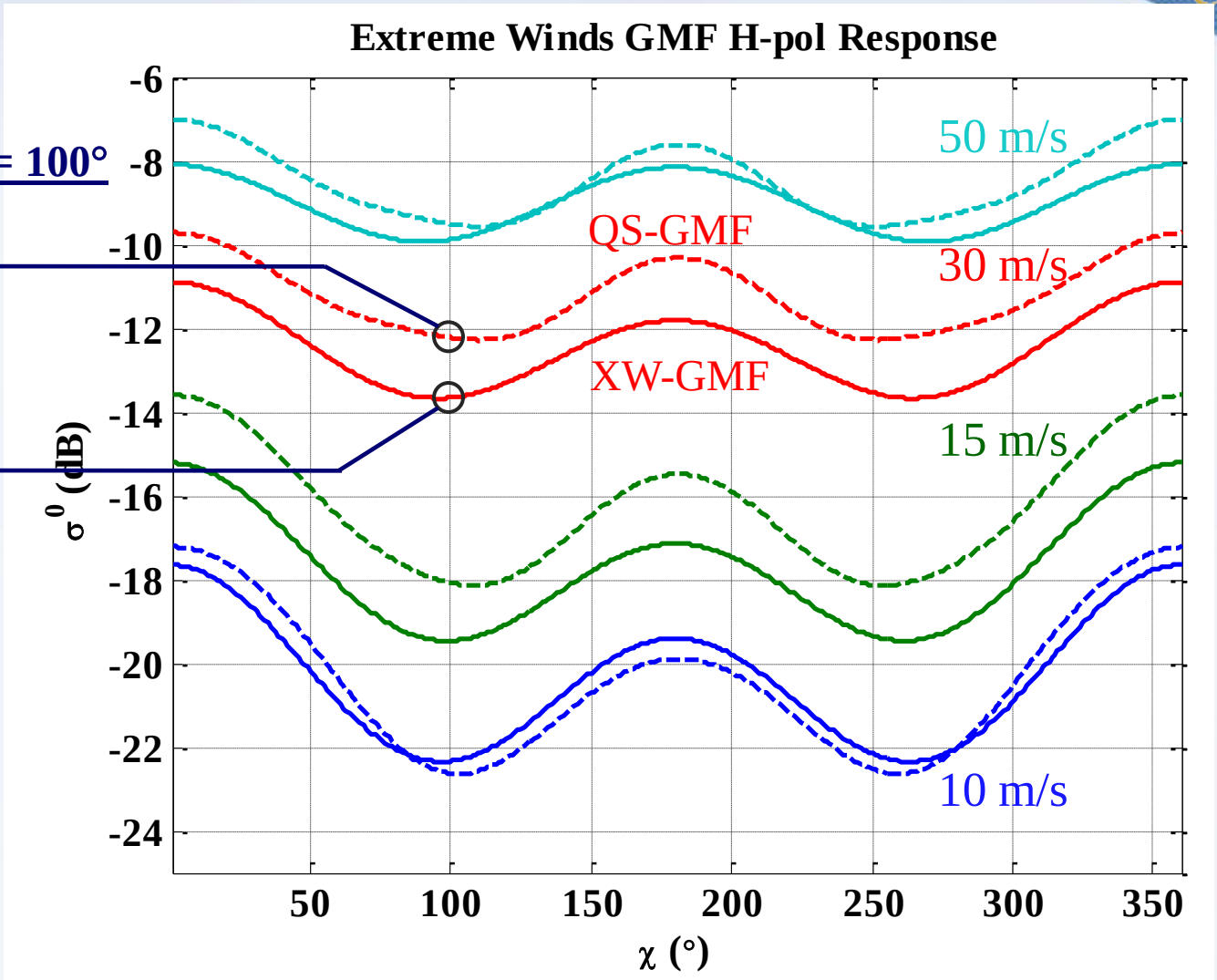
χ

XW-GMF & QS-GMF Comparison

WS = 30 m/s @ χ = 100°

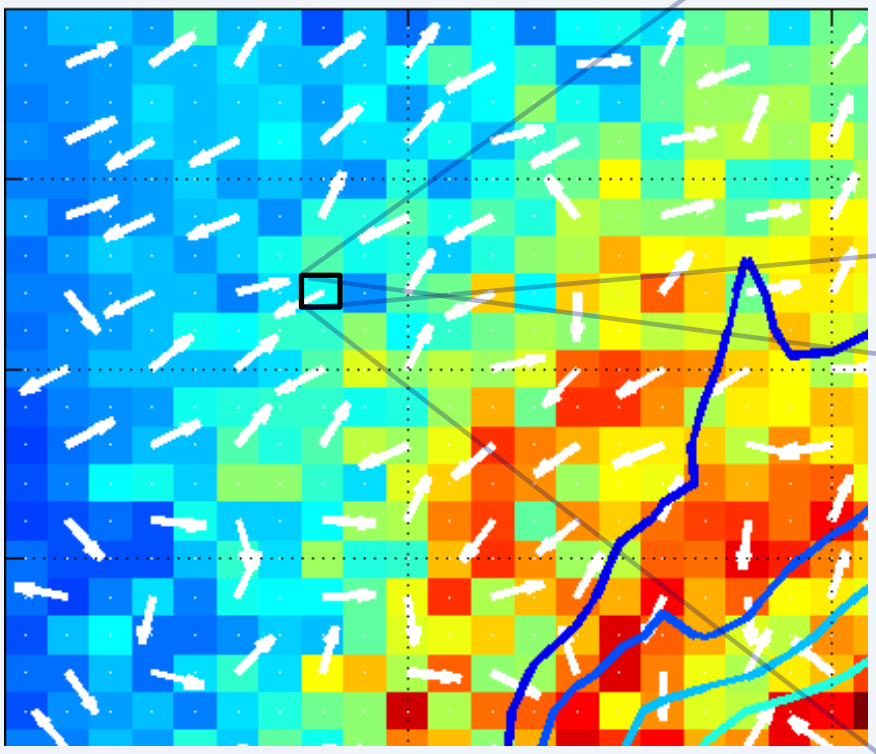
QS-GMF:
-12 dB = 0.063

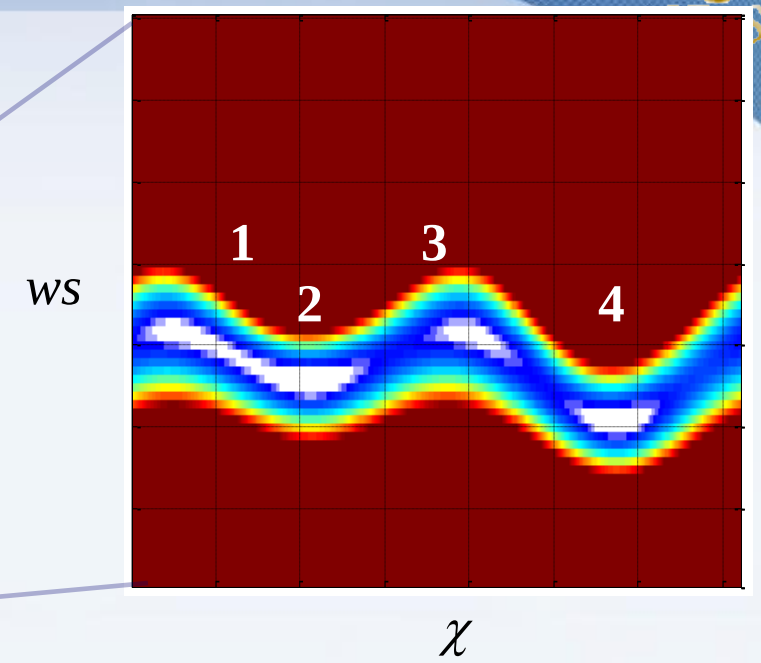
XW-GMF:
-13.5 dB = 0.045

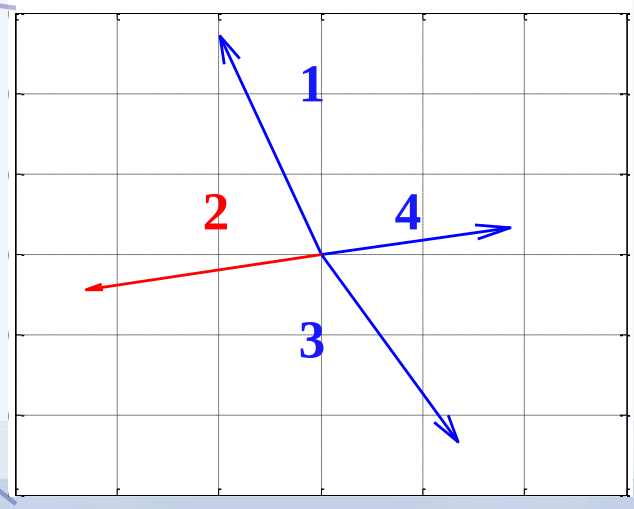


Hurricane OVW Retrieval

- MLE wind vectors retrieval performed for all WVC's



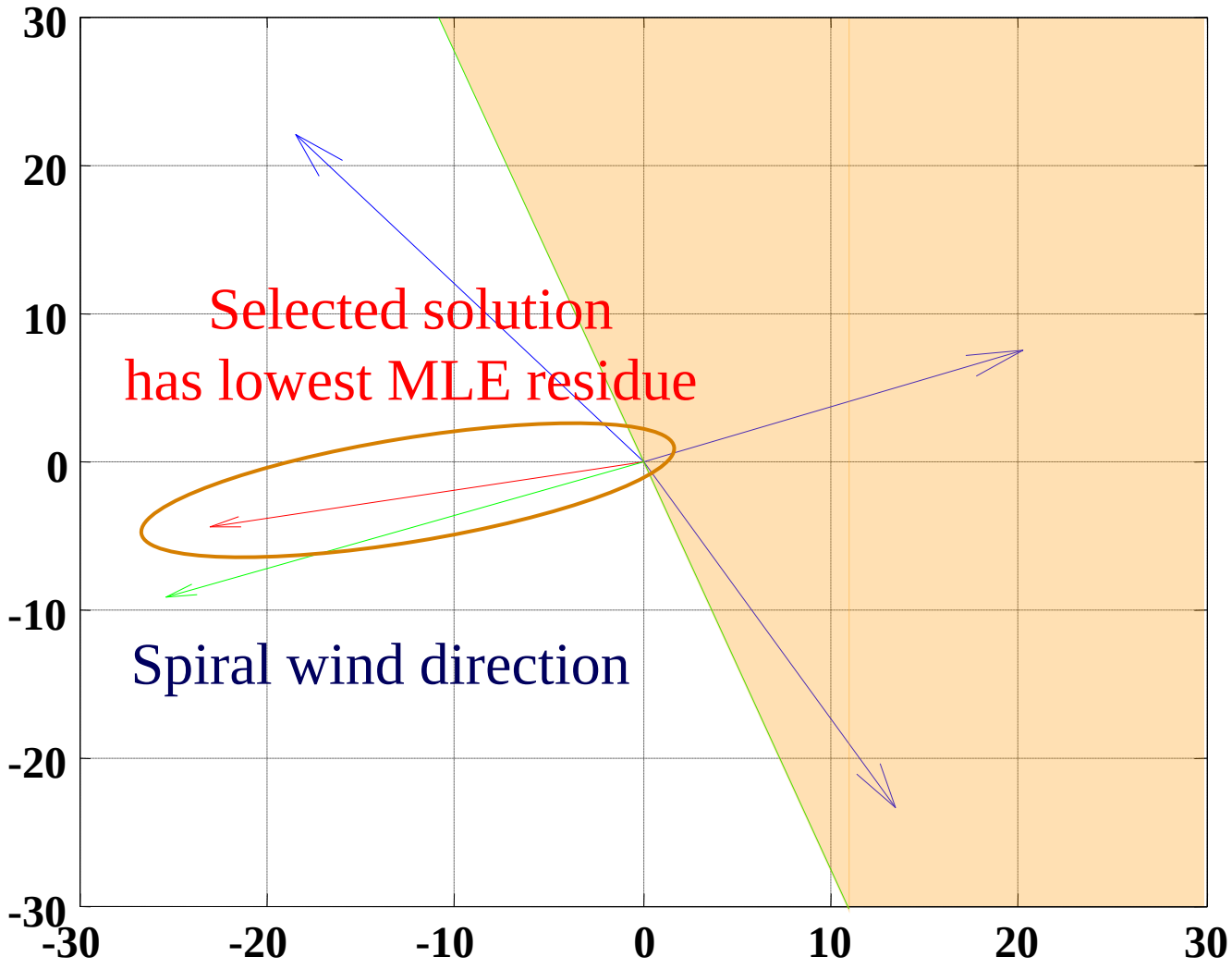




Spiral Wind Direction De-aliasing

- TC in northern hemisphere rotates counter-clockwise (CCW) about storm center
  - Storm center from NHC
- Majority of incorrect solutions can be eliminated by comparing to CCW direction model
- Remainder of solutions are ranked according to residue
- *Lowest* accumulative residue in WVC selected as "solution"

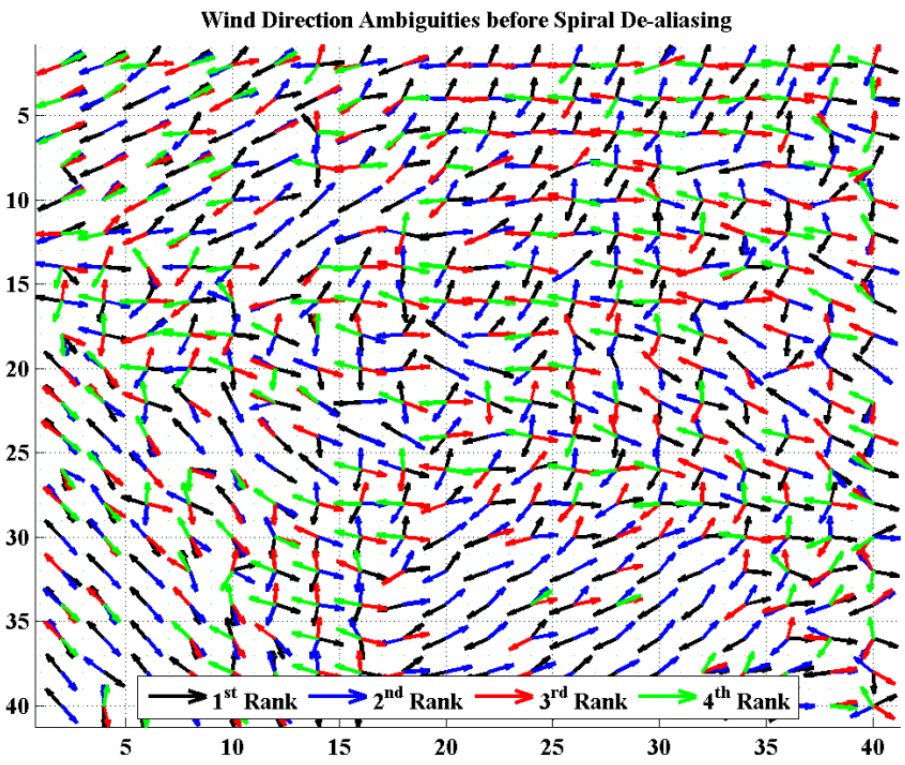
Spiral De-aliasing

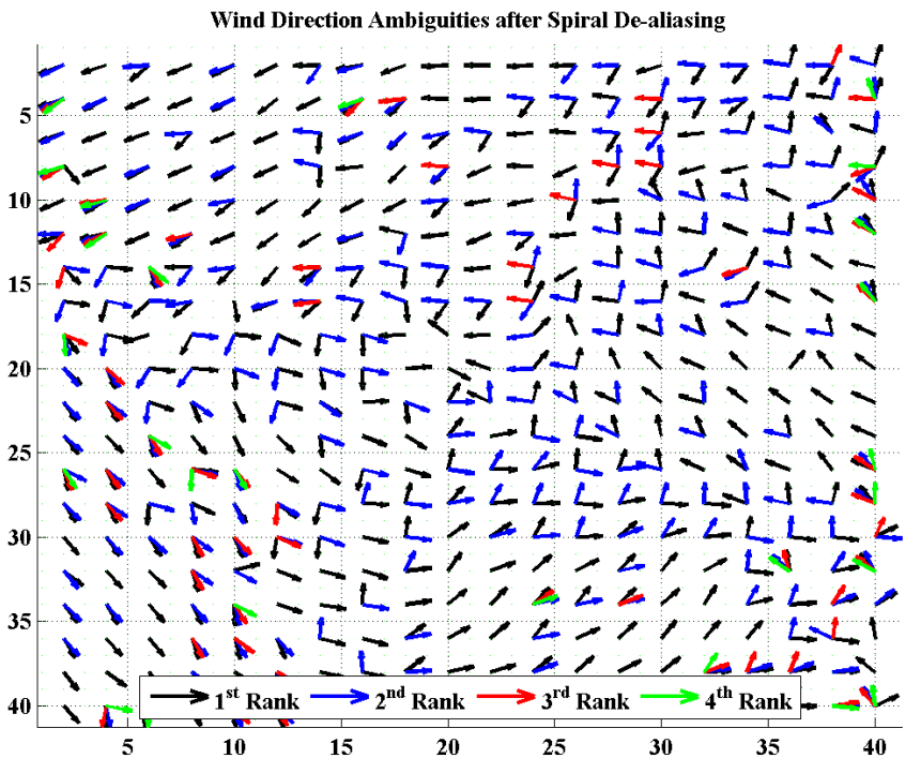


Spiral De-aliasing

All Aliases

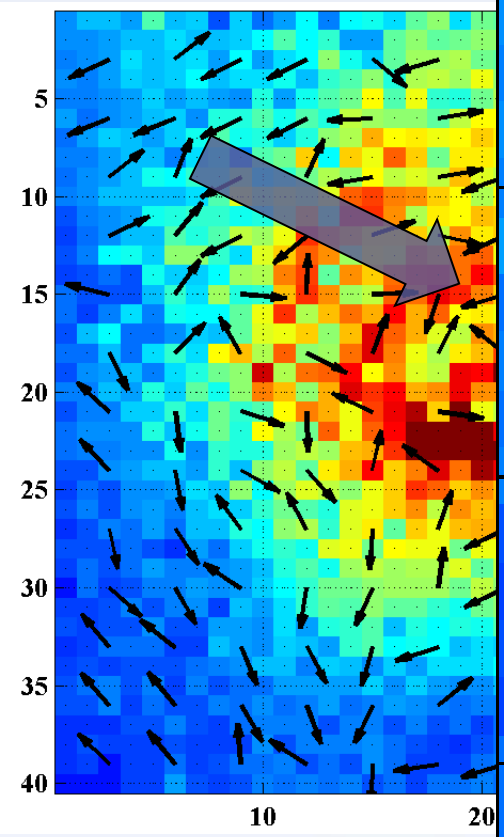
After Spiral De-aliasing

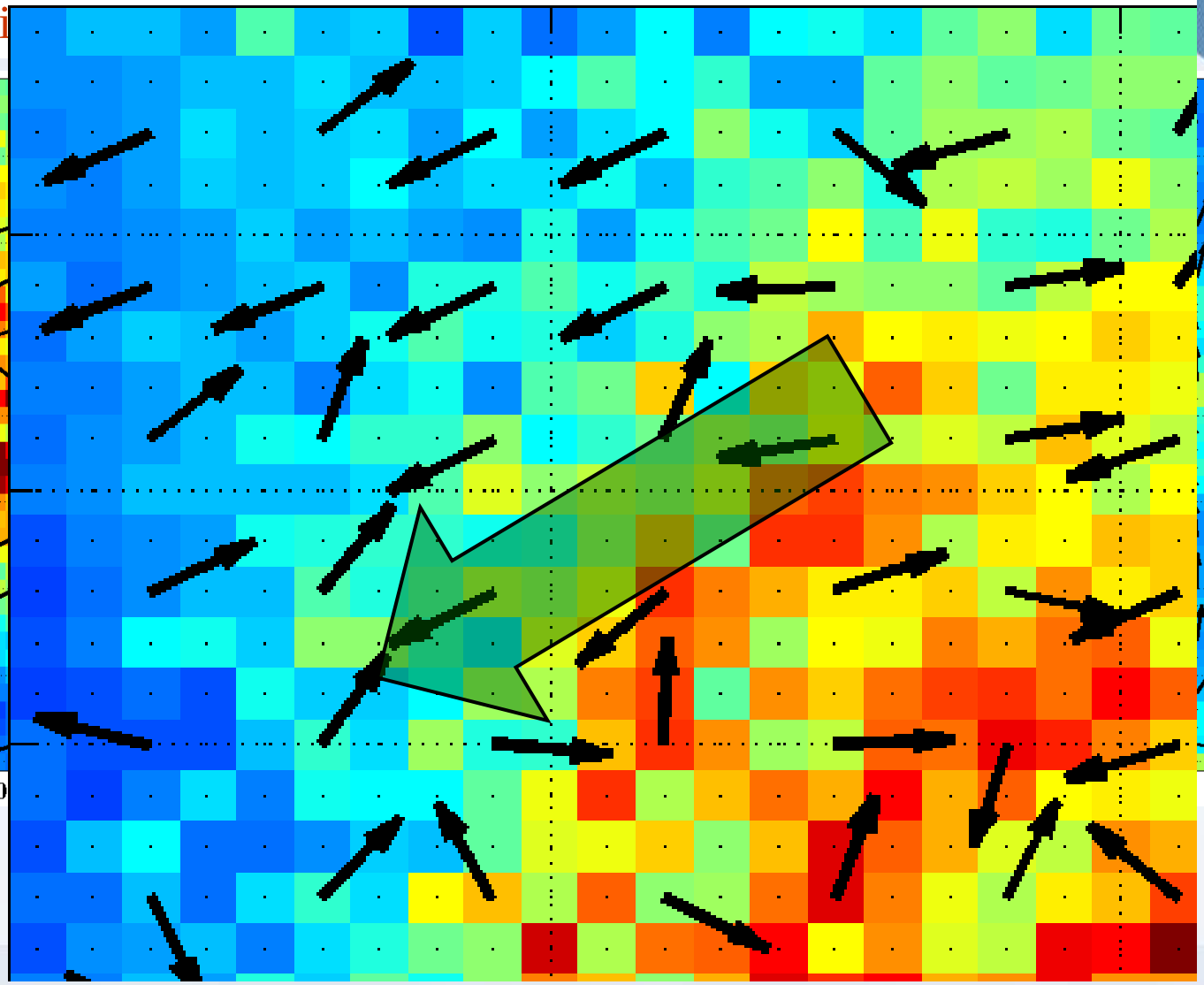




Ambiguity Removal in TC

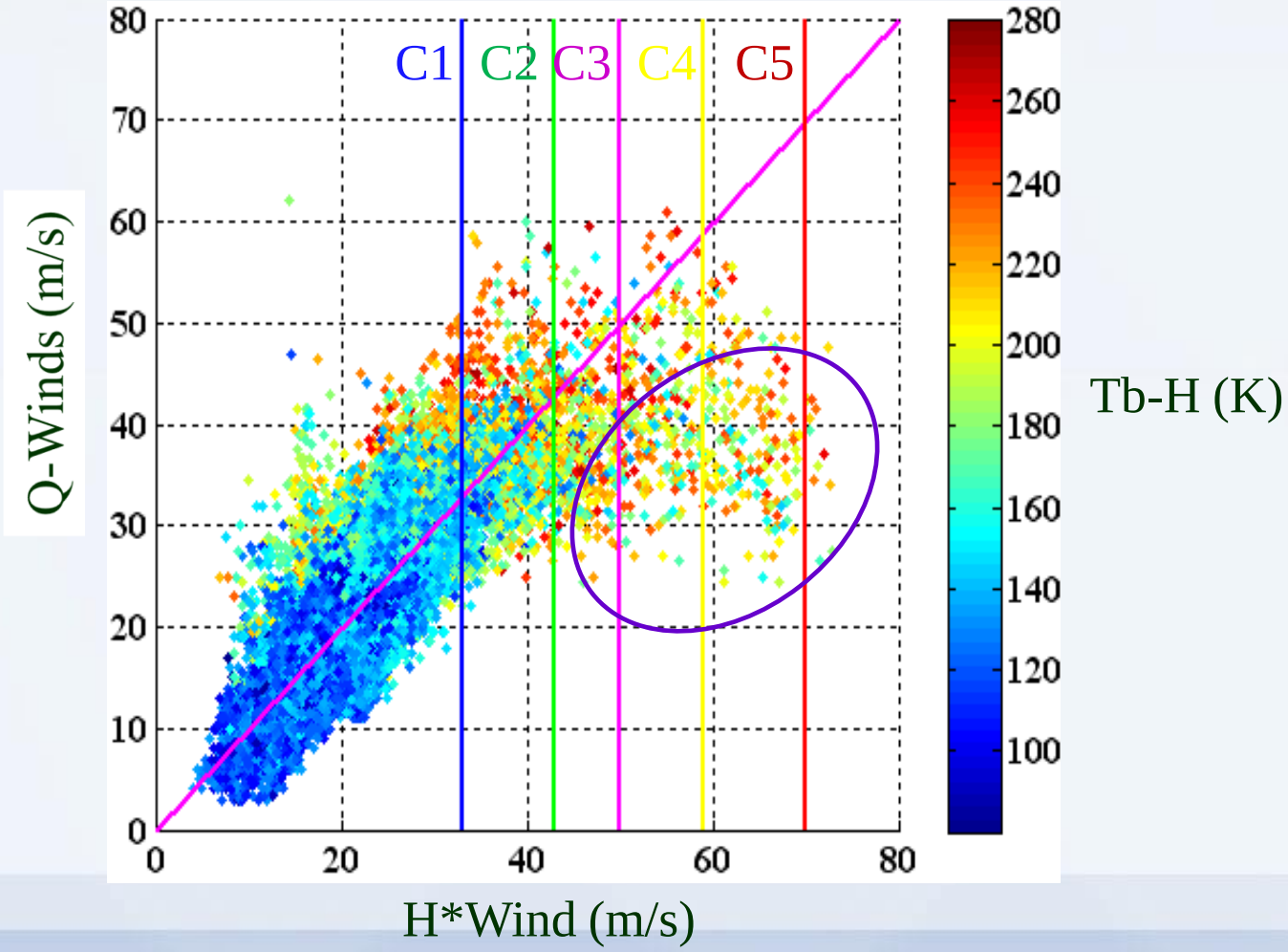
1st Solution Wi



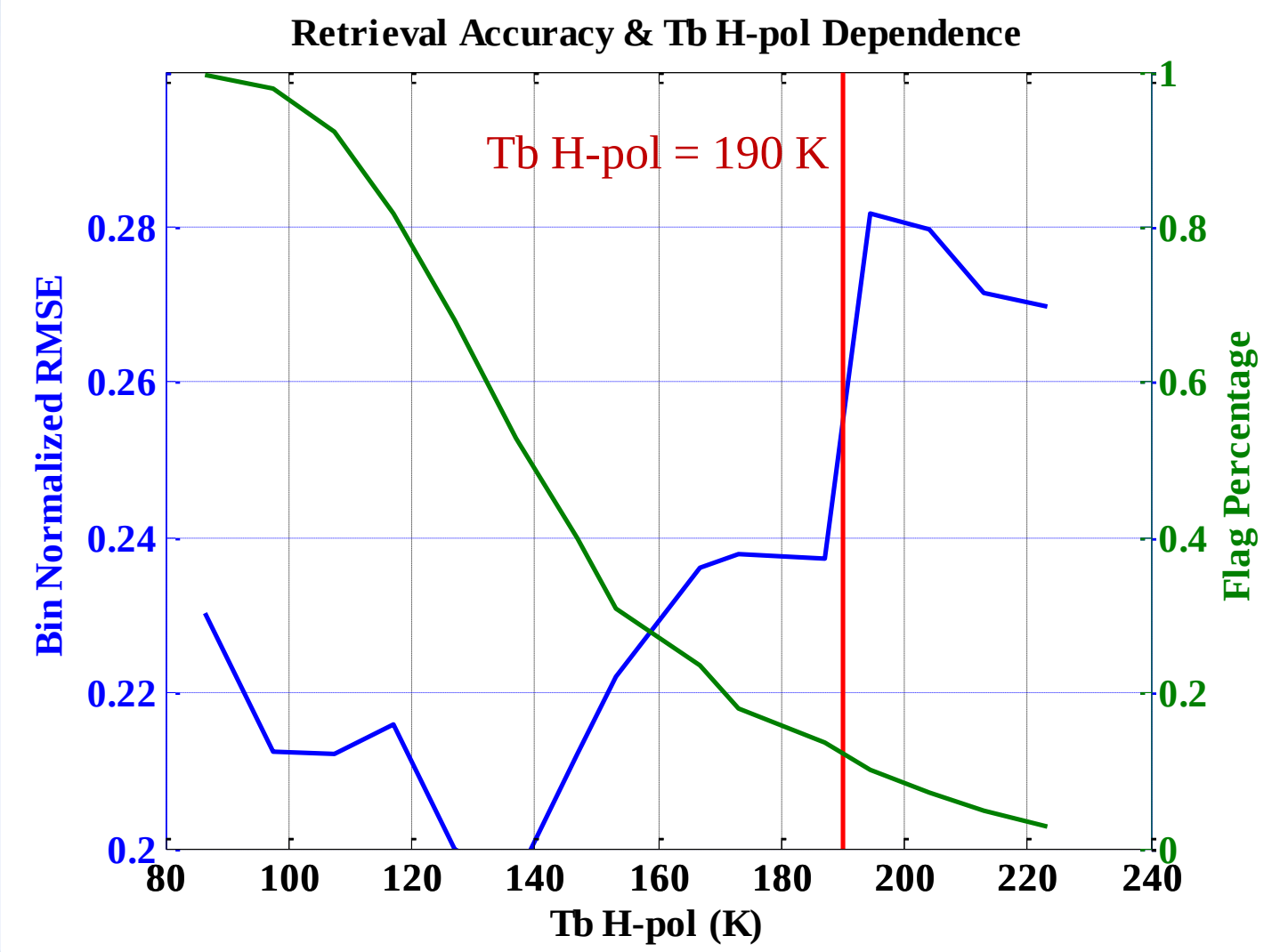


Excess-rain Flagging

- Quality control "*excess-rain*" flagging algorithm was developed to discard low confidence retrieved WVC's



Optimal Rain Flagging Threshold



Tb H-pol = 190 K yields NRMSE < 0.25 & % Flag ~ 15%

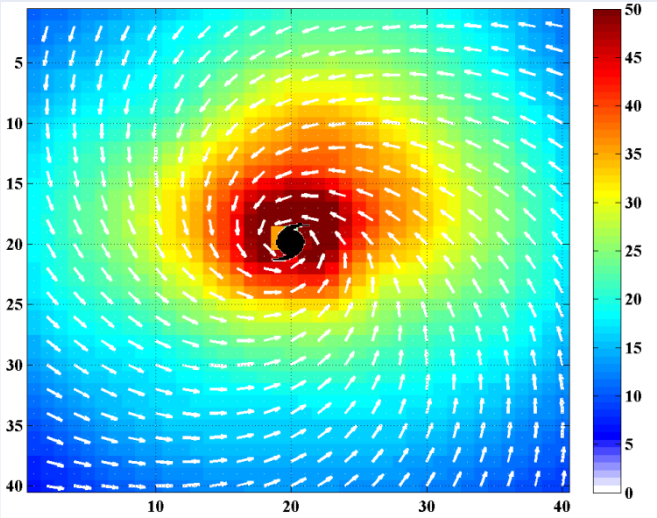
Results

- Wind Speed Comparison
- Wind Direction Comparison
- Contribution of GMF
- Effectiveness of Rain Correction
- Rain Flagging
- TC radii Comparison

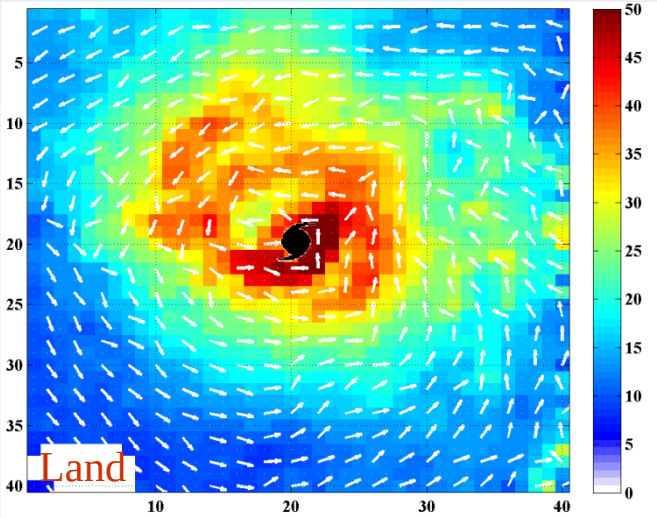
Wind Speed Evaluation

Hurricane Cat-4 Fabian September 2nd 2003

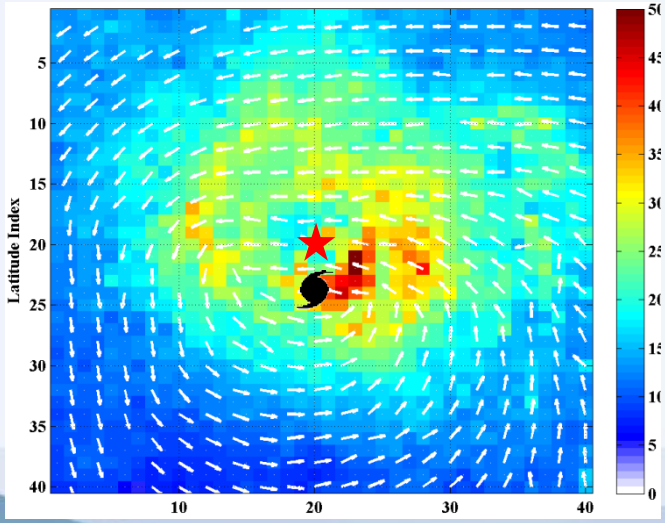
H*Wind



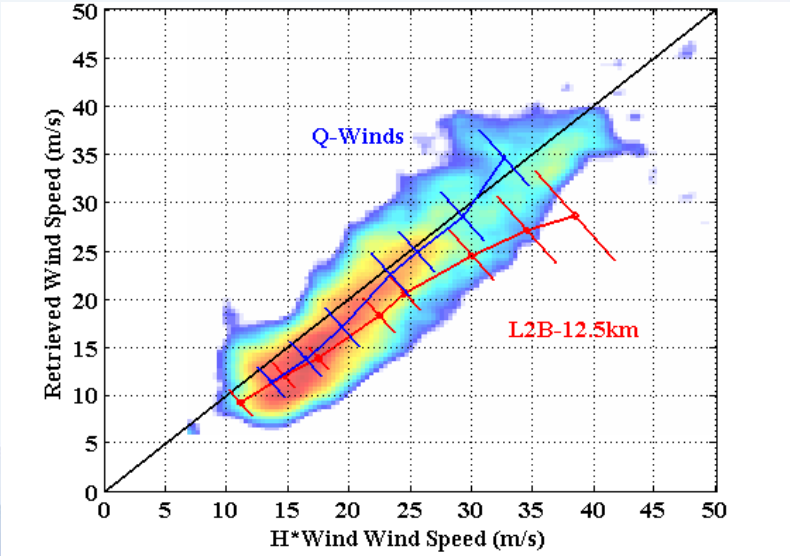
Q-Winds



L2B-12.5km



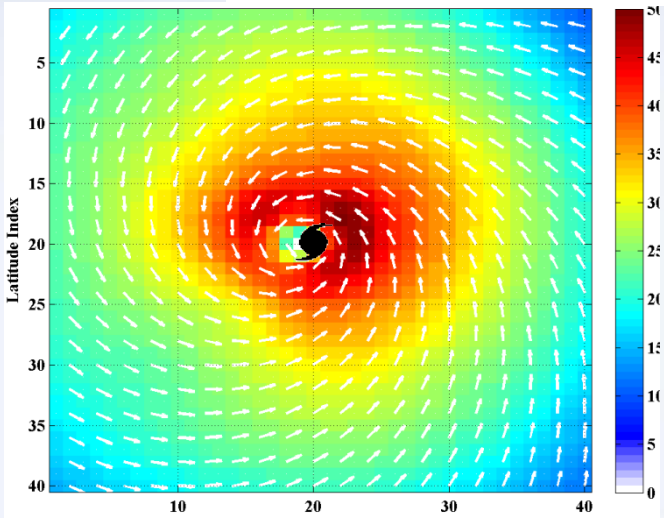
Wind Speed Scatter Plot



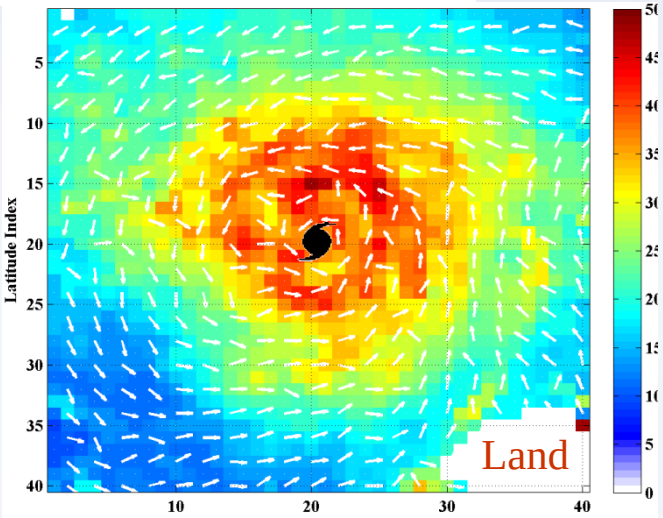
Wind Speed Evaluation

Hurricane Cat-3 Katrina August 28th 2005

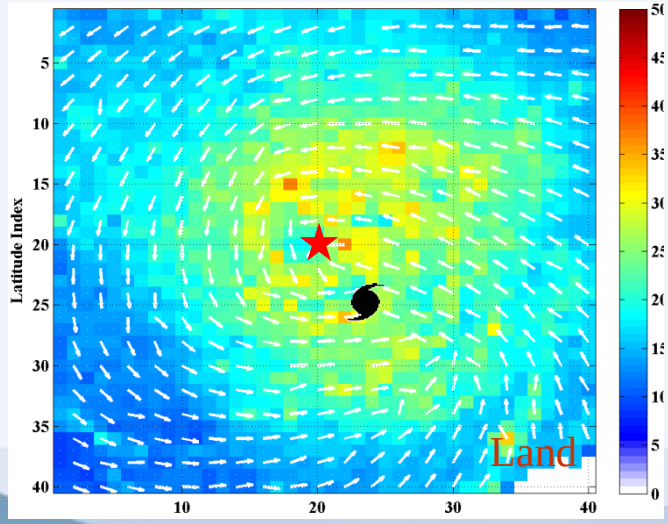
H*Wind



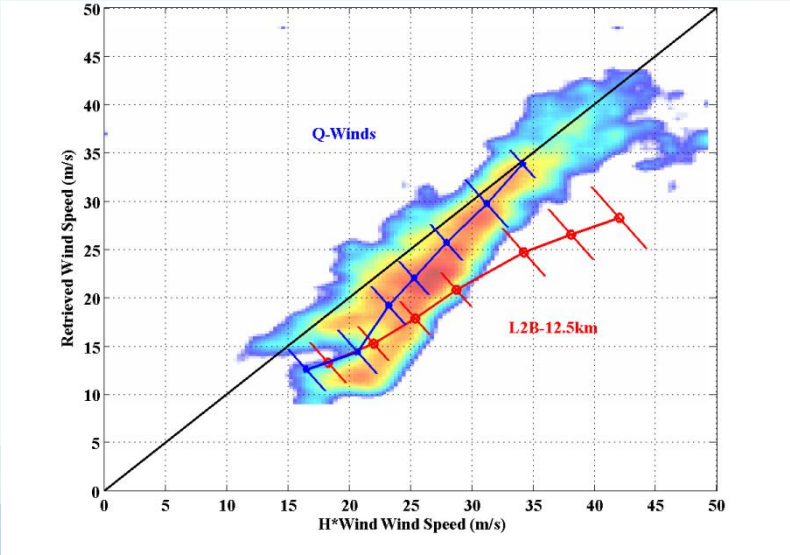
Q-Winds



L2B-12.5km



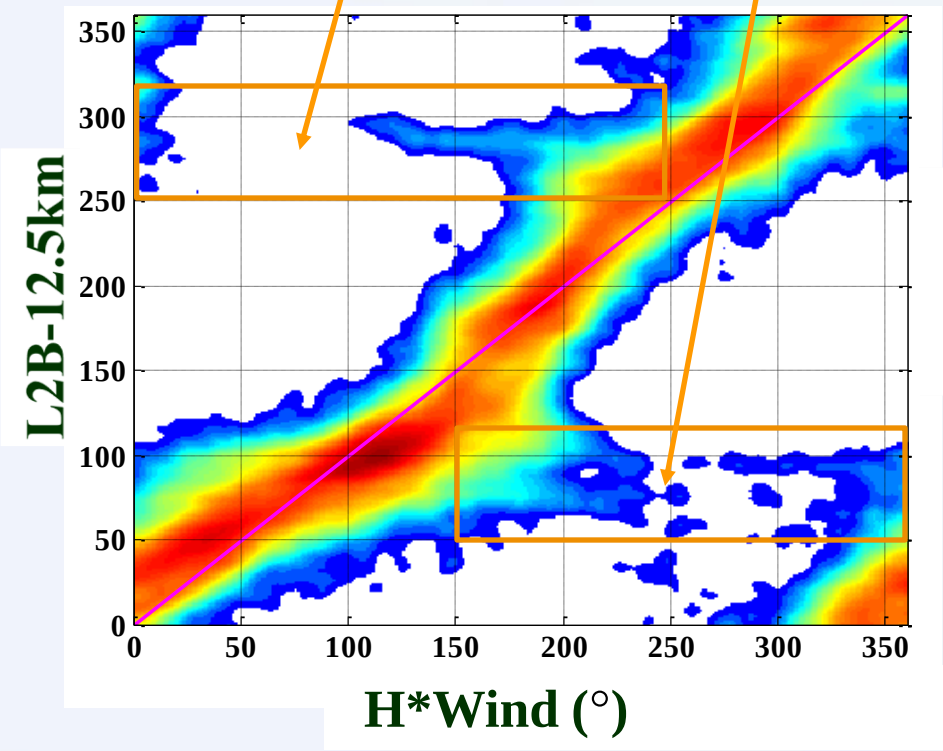
Wind Speed Scatter Plot

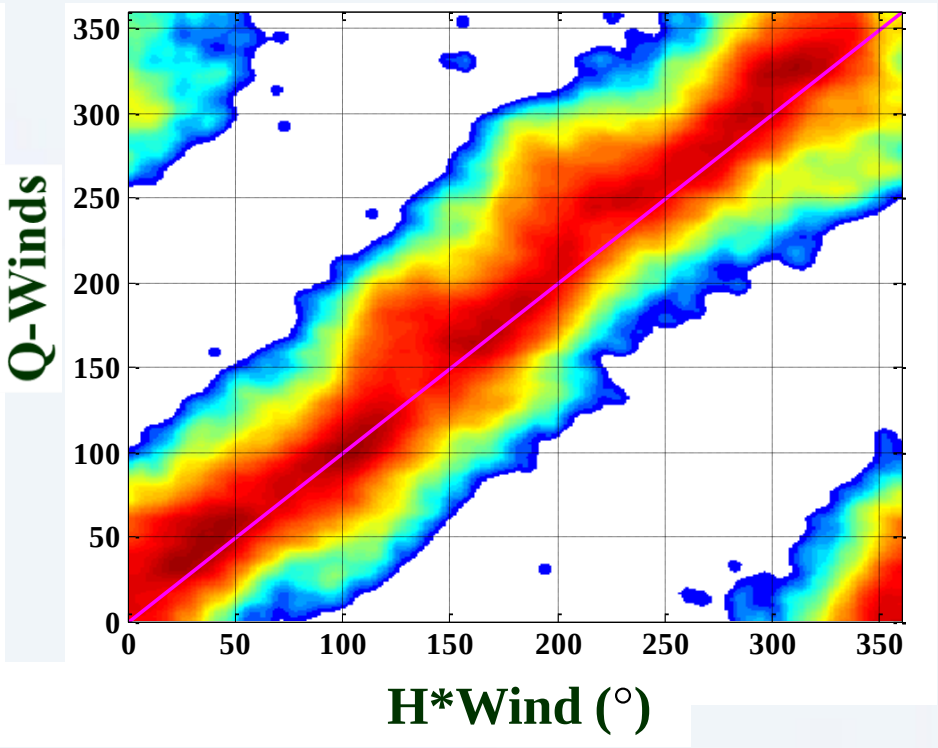


Wind Directions Comparison for 18 Revs

L2B-12.5km **Q-Winds**

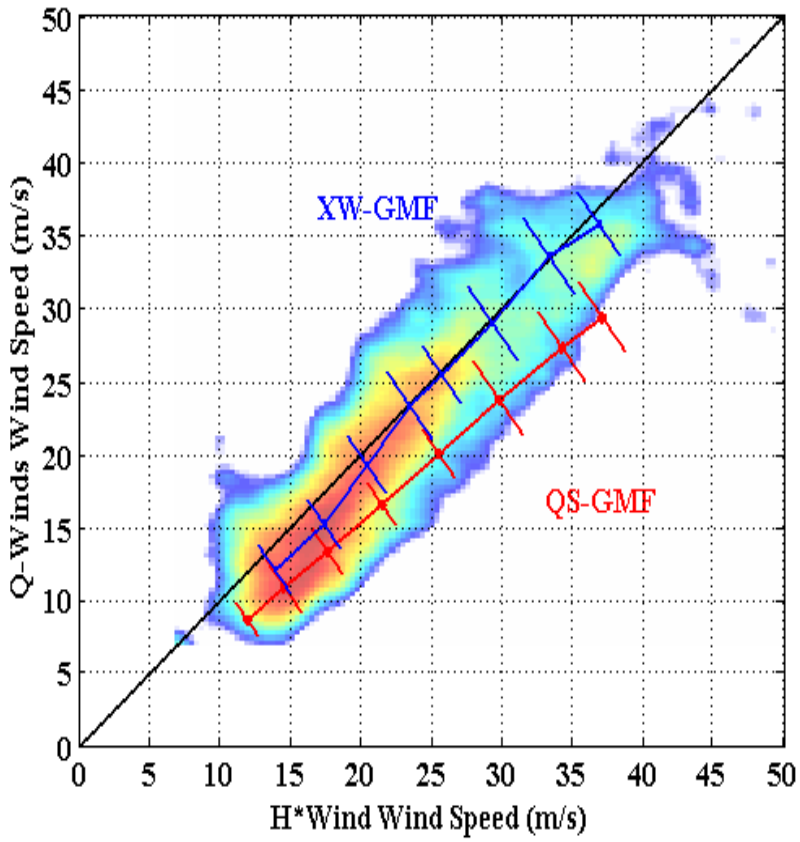
Incorrect wind direction due to rain contamination



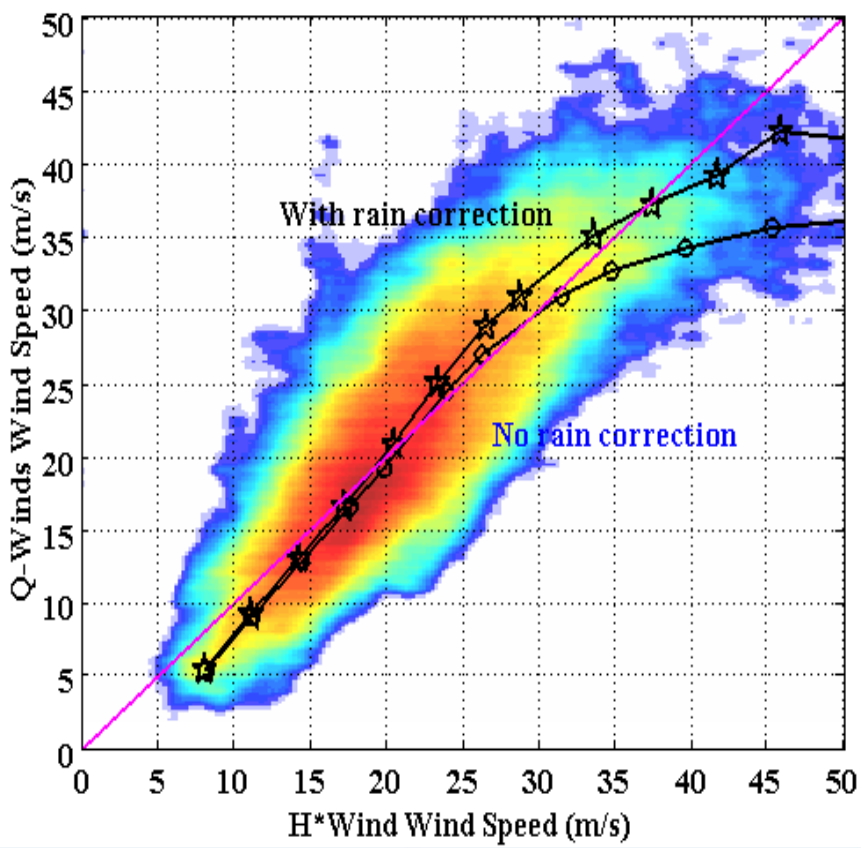


Contributions from GMF & Rain Correction

GMF



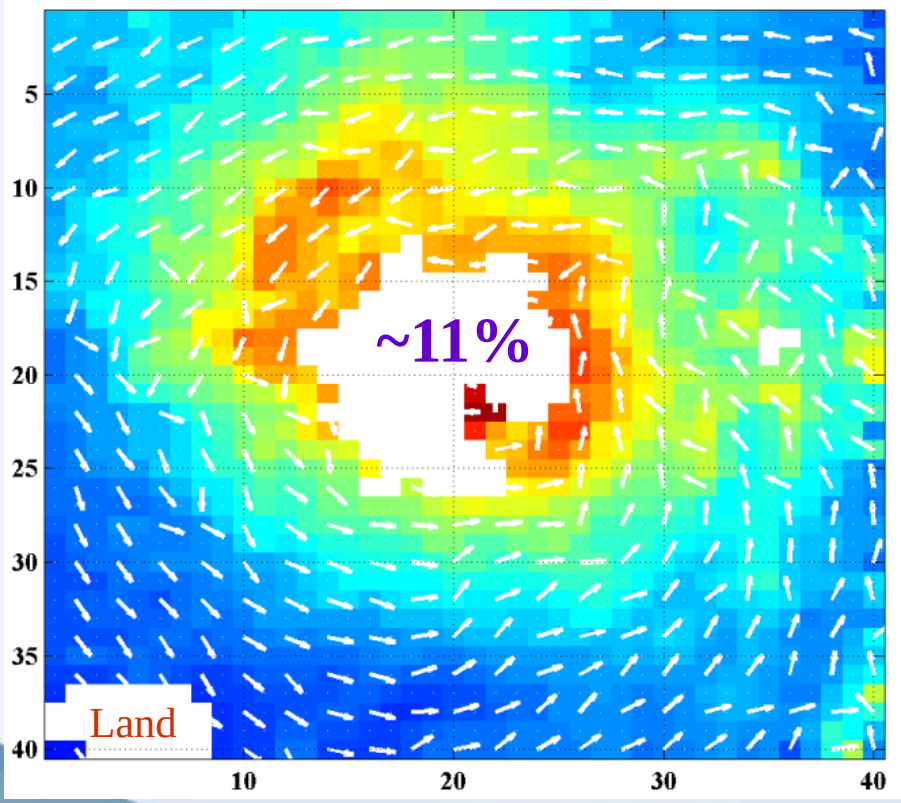
Rain Correction



Rain Flags Comparison

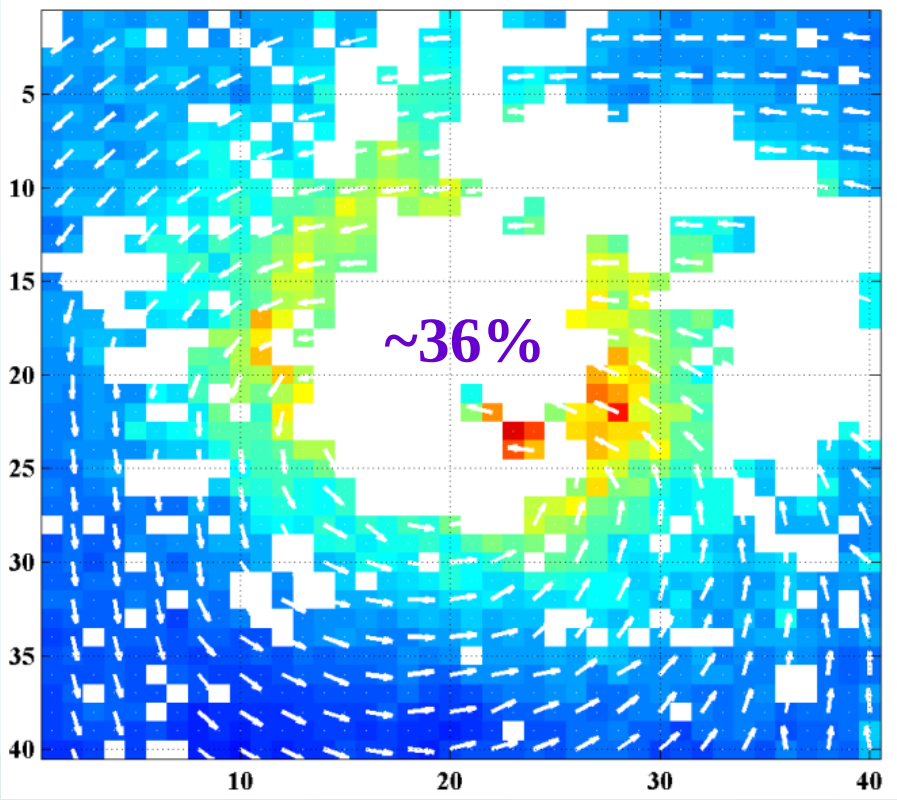
Q-Winds

Excess-rain Flag

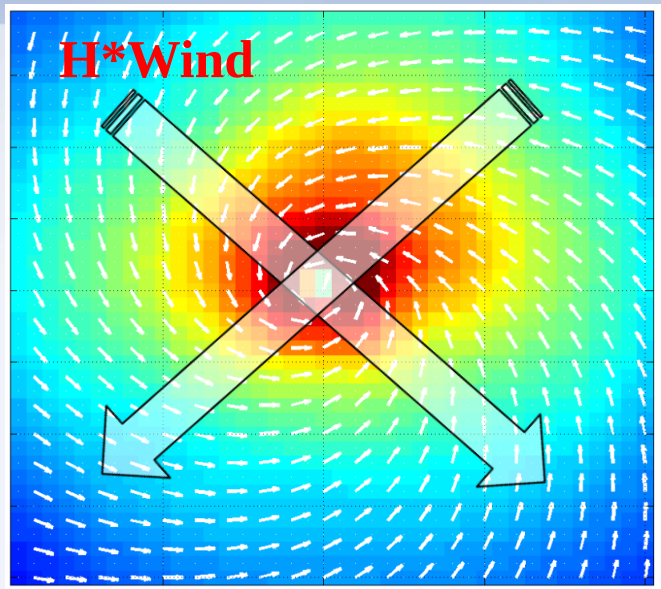


L2B-12.5km

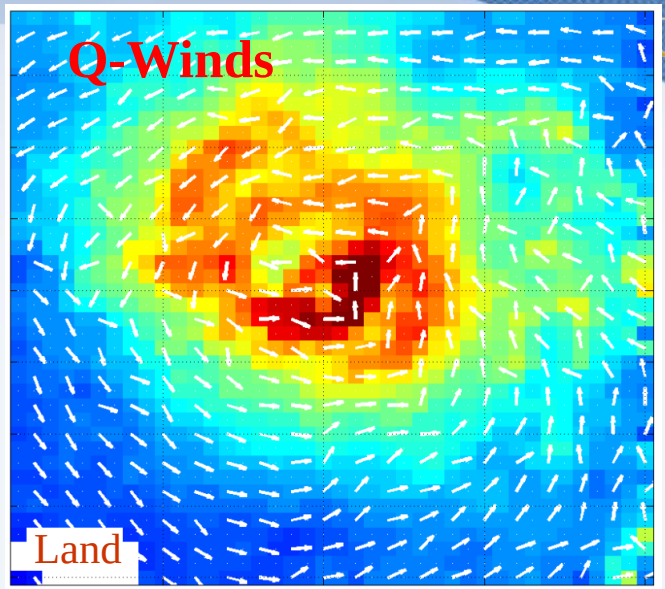
Multidimensional Histogram (MUDH)



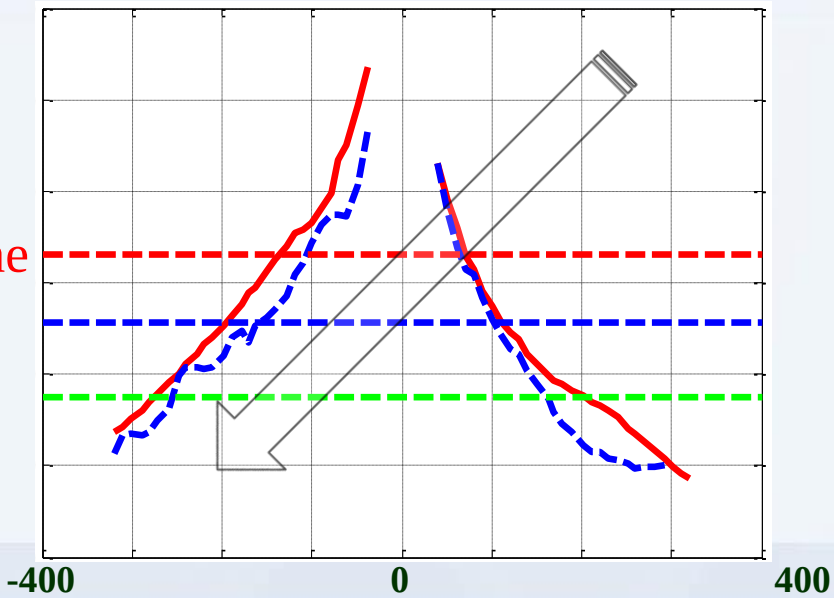
TC Radii Comparison



Fabian
21898

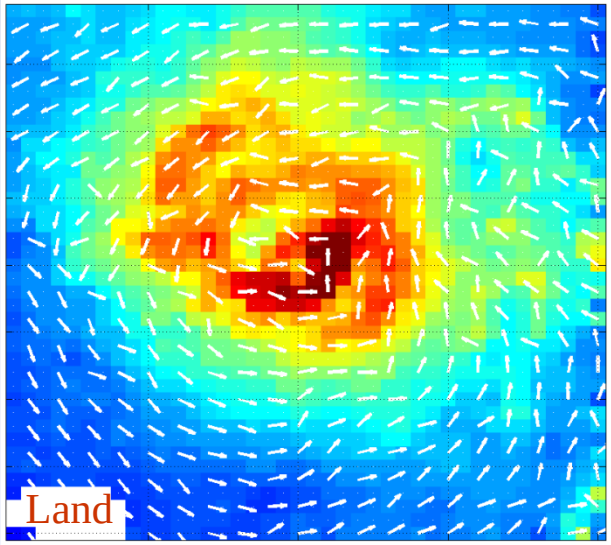


Hurricane
Storm
Gale

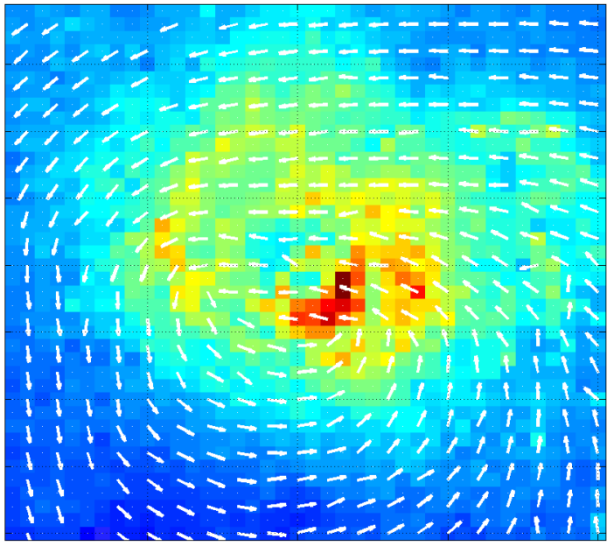


Hurricane Fabian C-4 (09/02/2003)

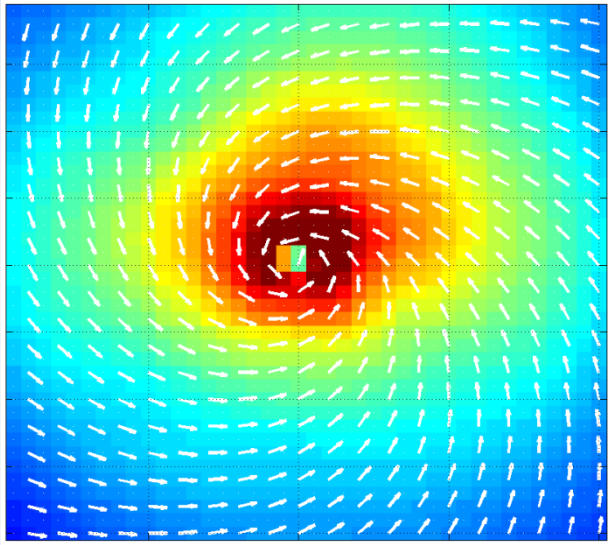
Q-Winds



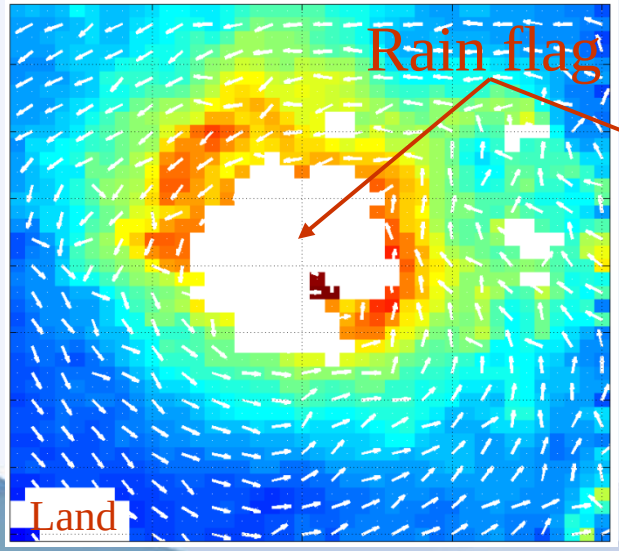
L2B-12.5km



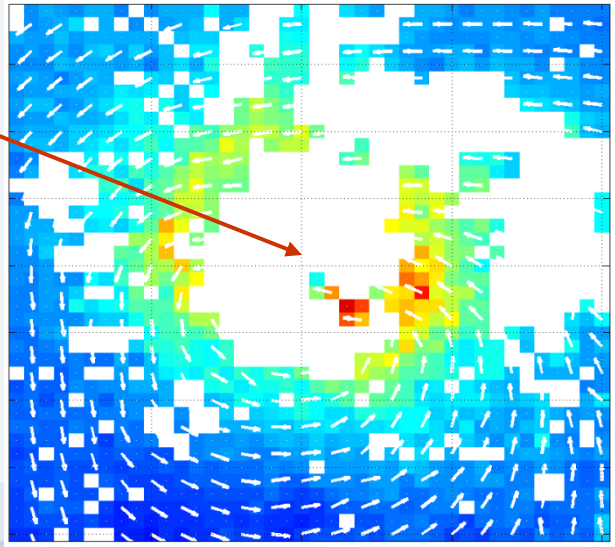
H*Wind

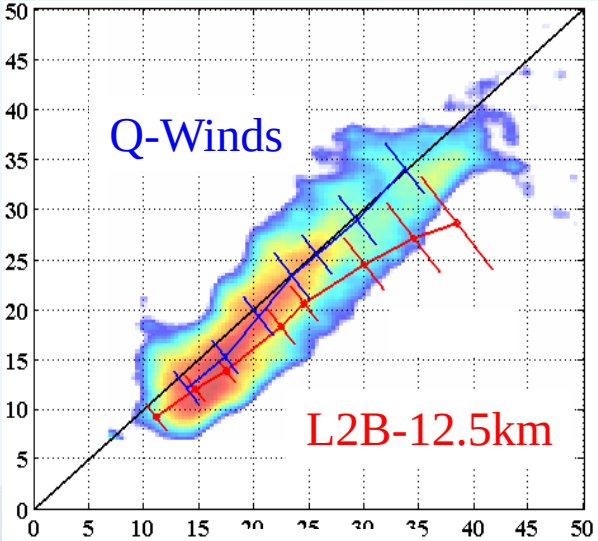


Q-Winds w/ Flags



L2B-12.5km w/ MUDH

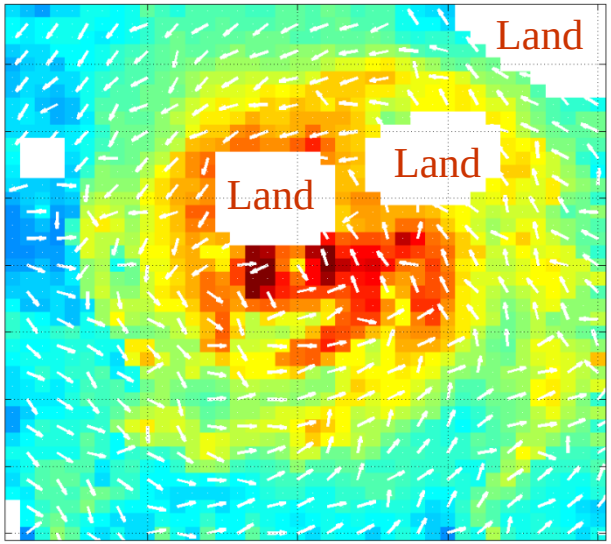




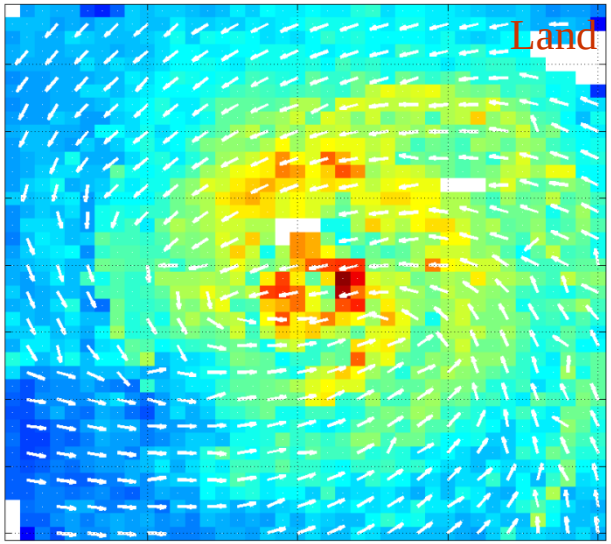
H*Wind

Hurricane Ivan C-4 (09/12/2004)

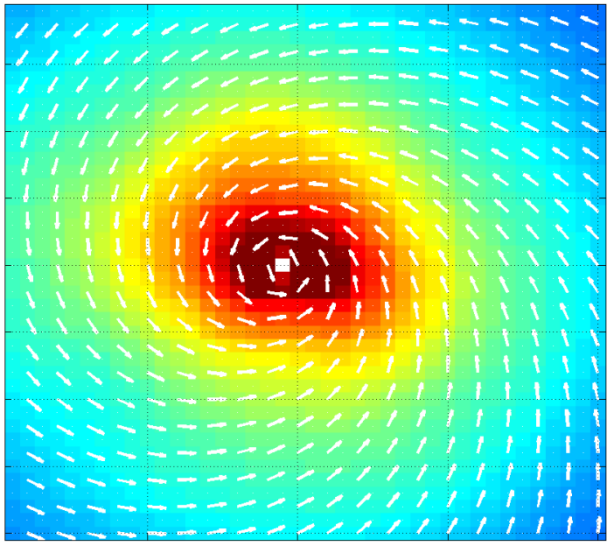
Q-Winds



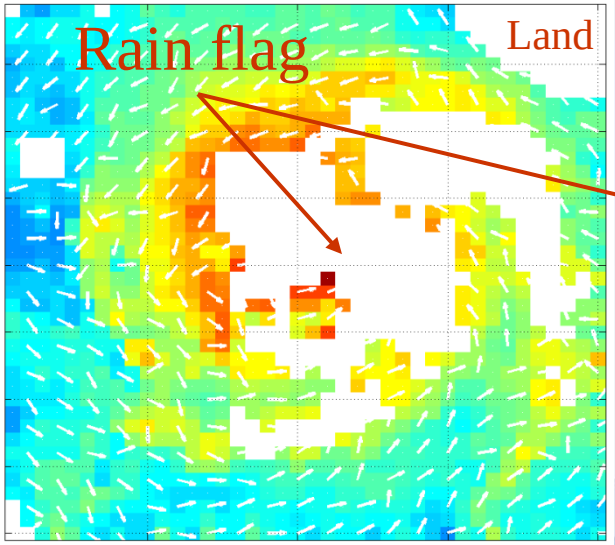
L2B-12.5km



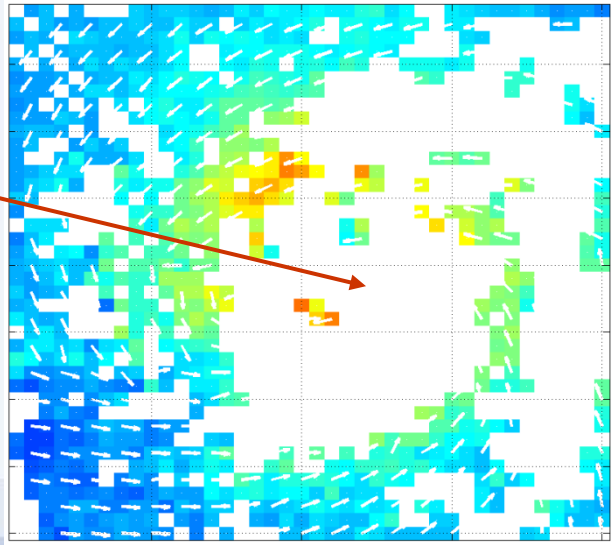
H*Wind

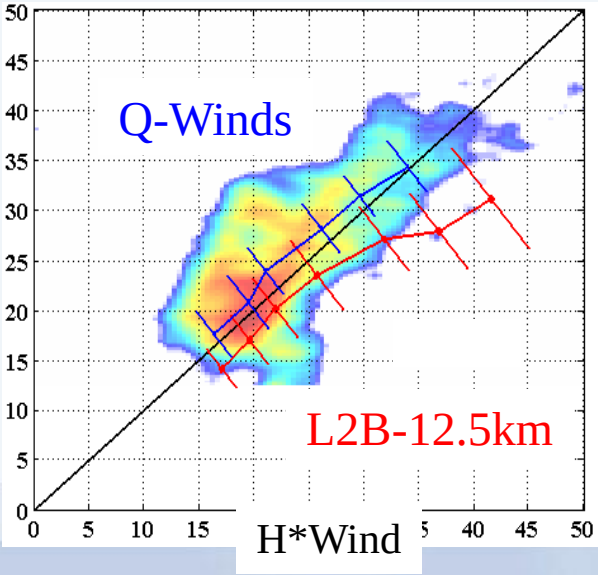


Q-Winds w/ Flags



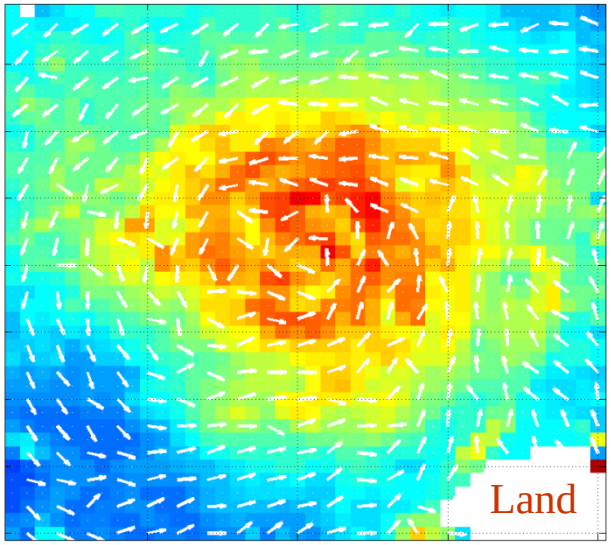
L2B-12.5km w/ MUDH



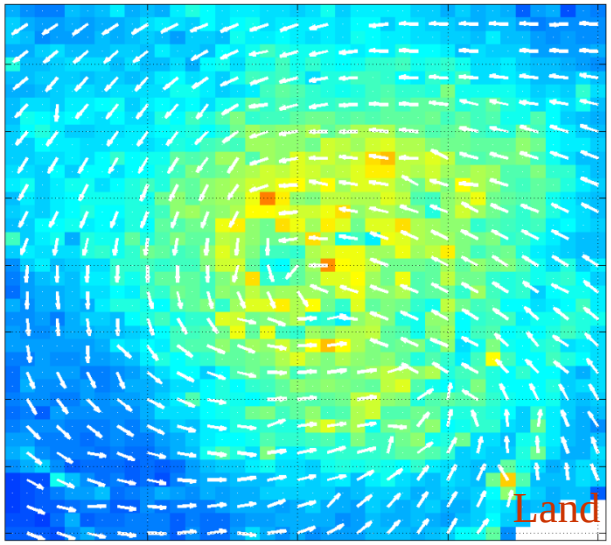


Hurricane Katrina C-3 (08/28/2005)

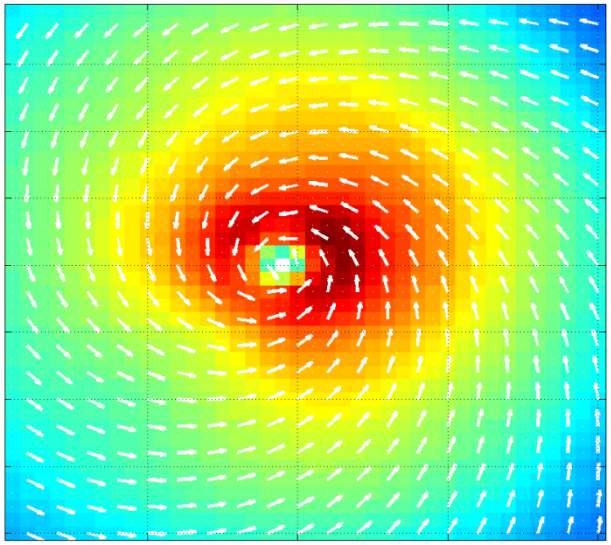
Q-Winds



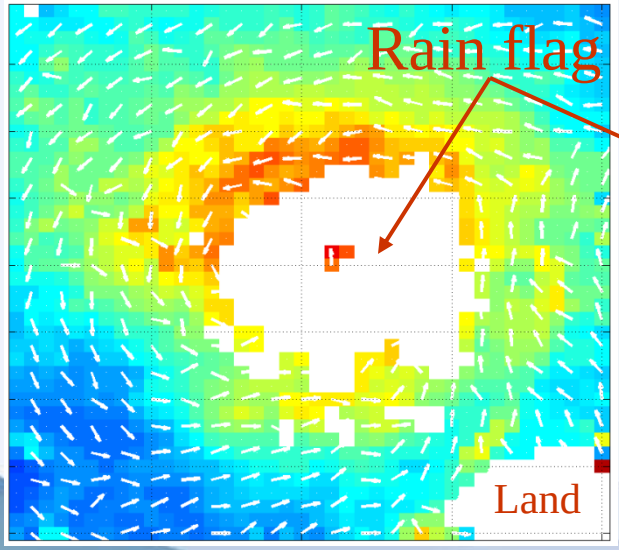
L2B-12.5km



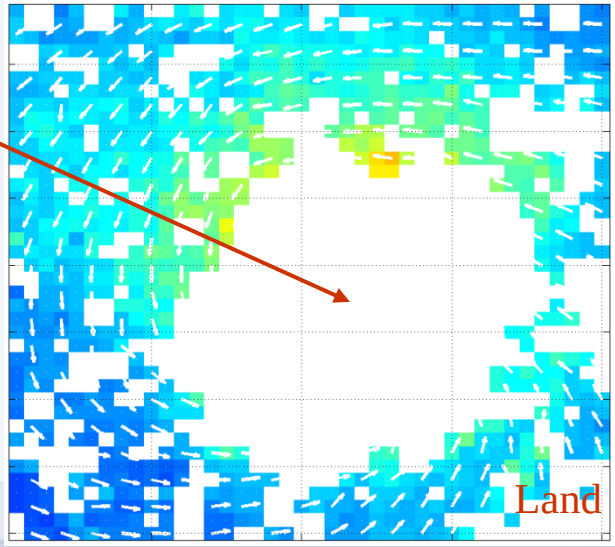
H*Wind

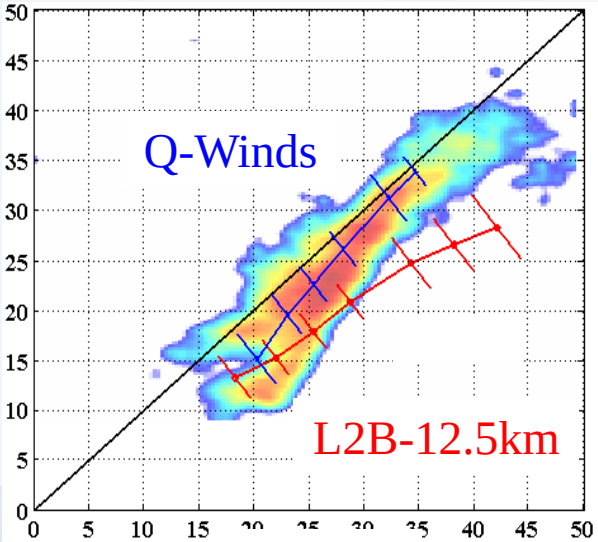


Q-Winds w/ Flags

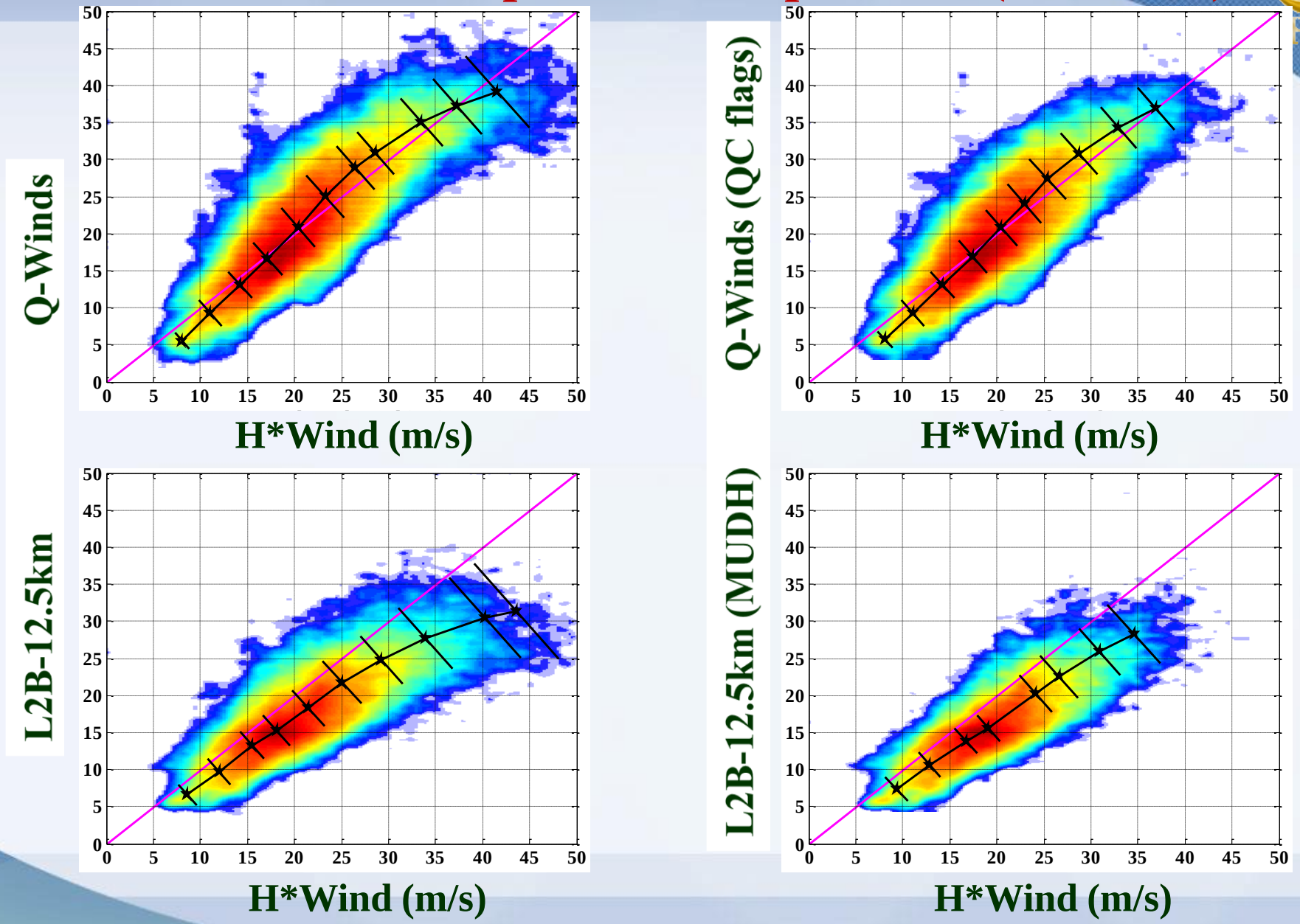


L2B-12.5km w/ MUDH



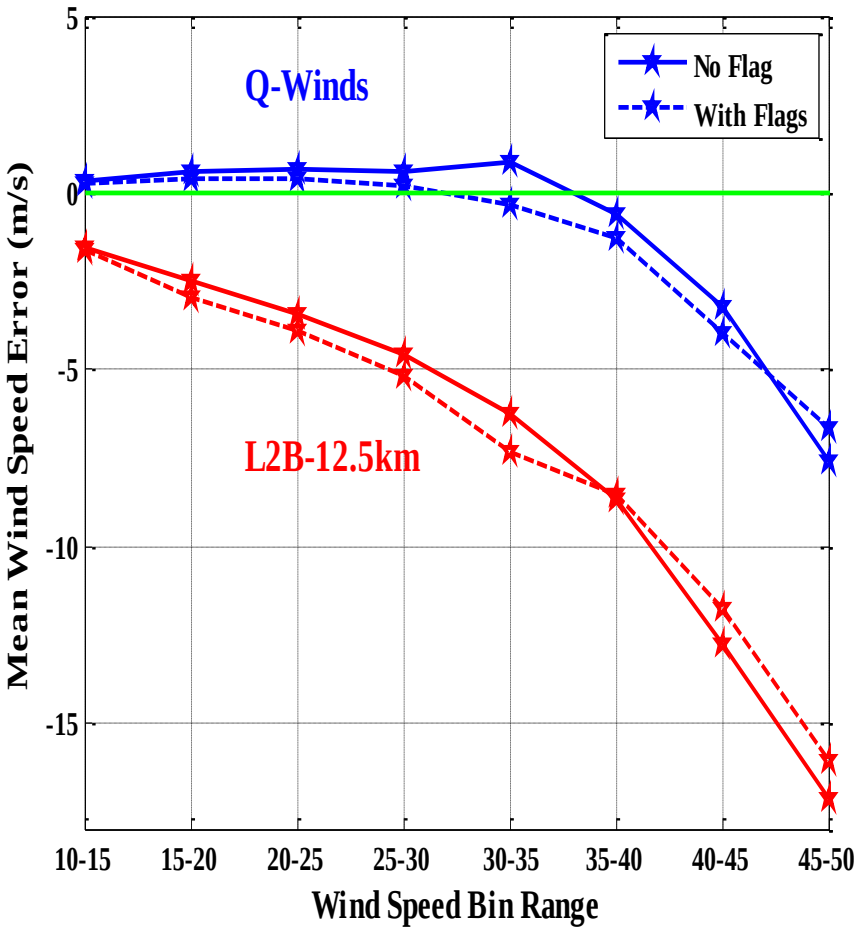


Gross Wind Speeds Comparison (18 Revs)

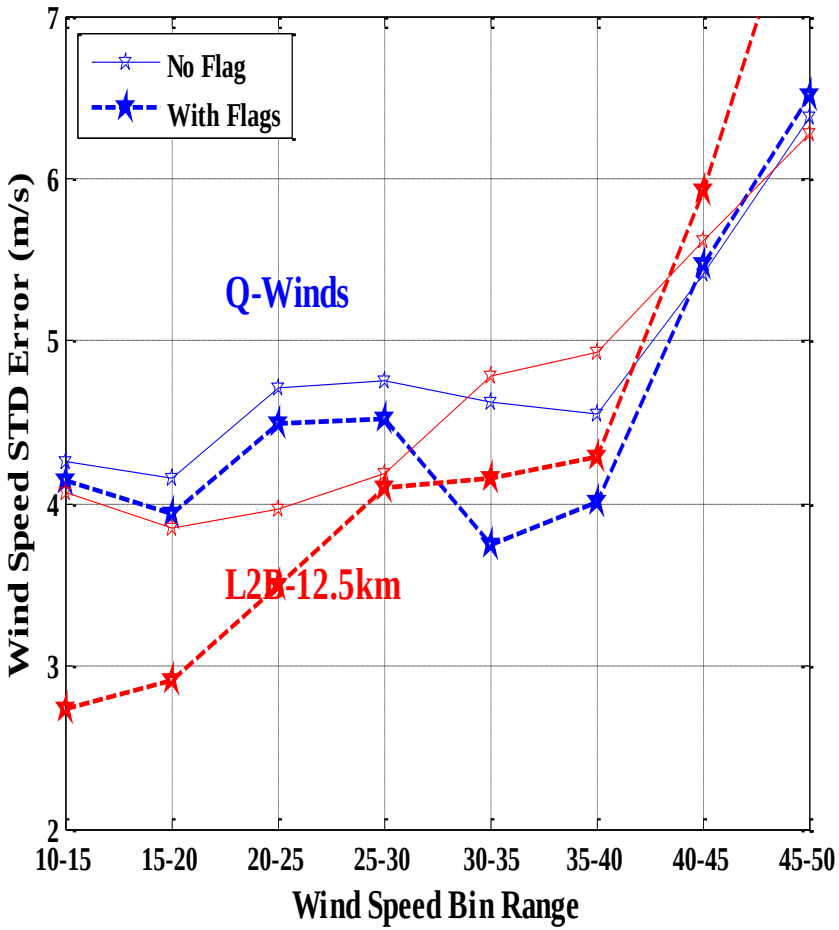


Wind Speed Performance Statistics

Mean



STD



Summary & Conclusions

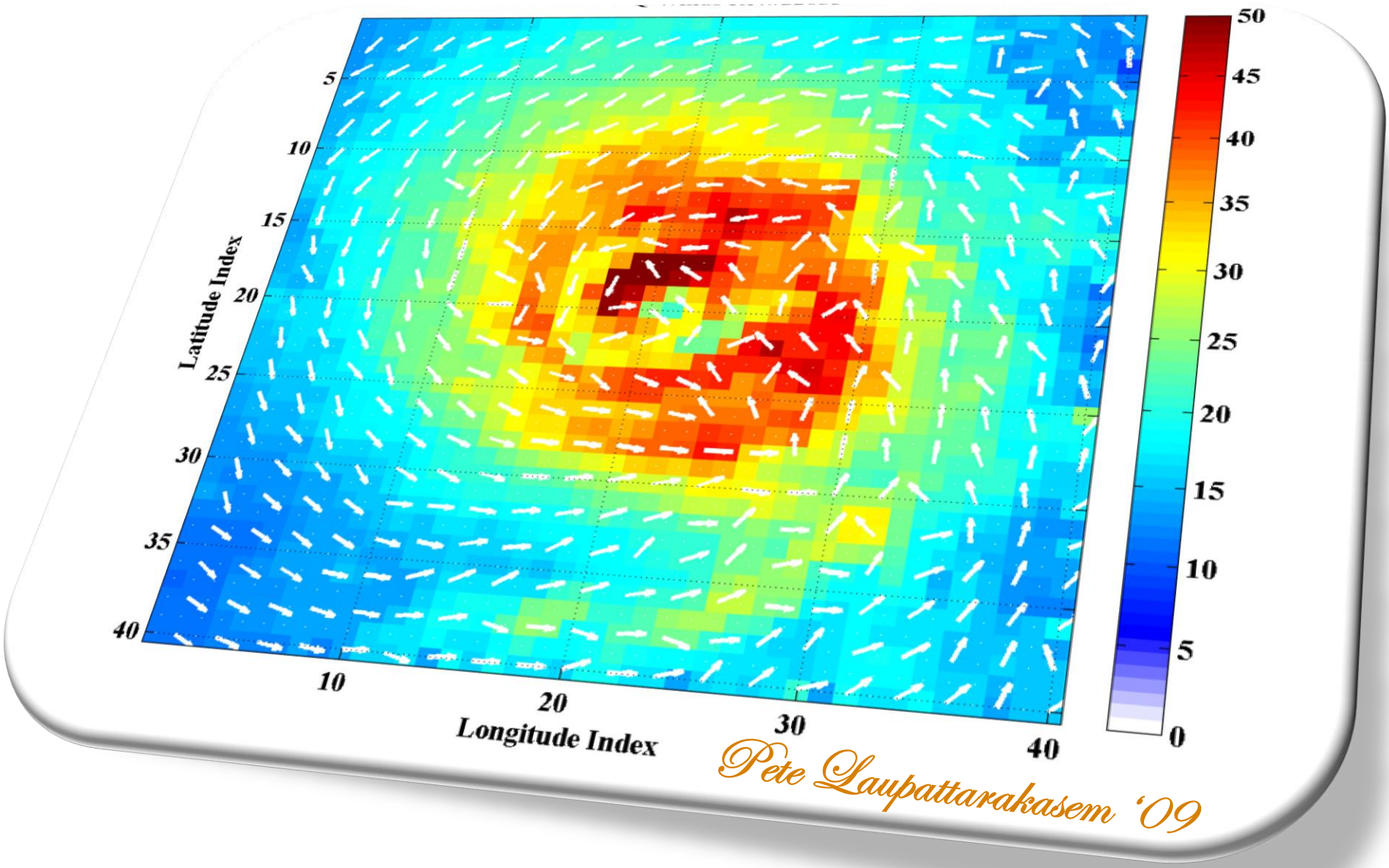
- Collocated passive QRad Tb provides:
  - Combined atmospheric transmissivity & rain volume backscatter
  - Excess-rain flags
- Wind speeds comparison to H*Wind:
  - Q-Winds:
    - Exhibits no apparent saturation
    - Agrees well in mean for speeds up to ~ 45 m/s
    - Standard deviation ~10%
  - JPL L2B-12.5km
    - Severe wind speed saturation

Summary & Conclusions

- Q-Winds compared to QuikSCAT L2B-12.5km:
  - Agrees well in mean for speeds < 15 m/s
  - Wind speed comparisons diverge when > 15 m/s with Q-Winds greater
  - Wind directions agree well for rain-free pixels
  - In light-moderate rain, Q-Winds directions are superior to L2B-12.5km
  - Both provide rain flags, but Q-Winds excess-rain flag removes fewer wind vectors than does L2B-12.5km MUDH
- Selected to incorporate Q-Winds in Joint-Hurricane Testbed (JHT) program for hurricane season 2010

List of Publications

- [1] **P. Laupattarakasem**, W. L. Jones, K. Ahmad, and S. Veleva, "Calibraion/validation of the SeaWinds Radiometer rain rate Algorithm," in *MTS/IEEE Oceans 2005*. Washington, D.C., 2005.
- [2] **P. Laupattarakasem**, S. Al Sweiss, W. L. Jones, and R. Roeder, "Conical-scanning active/passive microwave remote sensor computer simulation," in *Proc. of the SPIE*. Orlando, FL, 2006.
- [3] S. Al Sweiss, **P. Laupattarakasem**, W. L. Jones, and R. Roeder, "A Ku-band active/passive wind vector retrieval over the ocean," in *Proc. IGARSS*, vol. 1, 2008, pp. 110-113.
- [4] **P. Laupattarakasem**, W. L. Jones, and C. C. Hennon, "SeaWinds hurricane wind retrievals and comparison with H*Wind surface winds analyses," in *Proc. IGARSS*, vol. 1. Boston, MA, 2008, pp. 284-287.
- [5] **P. Laupattarakasem**, W. L. Jones, C. C. Hennon, P. G. Black, J. R. Allard, and A. R. Harless, "Q-Winds satellite hurricane wind retrievals and H*Wind comparisons," in *28th Conference on Hurricanes and Tropical Meteorology, American Meteorological Society*. Boston, MA, 2008.
- [6] **P. Laupattarakasem**, W. L. Jones, C. C. Hennon, J. R. Allard, and A. R. Harless, "Improved hurricane ocean vector winds using SeaWinds active/passive retrieval," *Submitted, IEEE Trans. Geosci. Rem. Sens.*, 2009.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Pete Laupattarakasem '09